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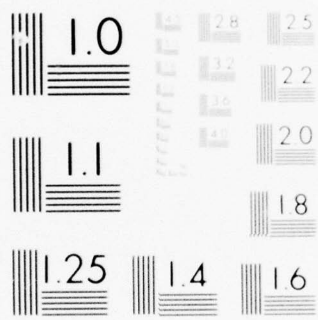
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A STUDY OF OPPORTUNISTIC REPLACEMENT
TACTICS FOR MODULAR JET
ENGINE MANAGEMENT

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LSSR 29-77A

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Opportunistic replacement for the F-100 engine has been previously studied to determine if an opportunistic replacement policy can save jet engine maintenance costs. The idea of opportunistic replacement is to replace an unfailed engine part before it fails while the engine is in the repair shop for some other reason (an opportunity). The costs that have been addressed in previous research are transportation, packing, manpower, parts, and depot overhaul costs. This study developed a method by which the impact of opportunistic replacement on spare engine and module inventory requirements can be assessed. Several different opportunistic replacement policies were studied and an optimum policy, based on the inventory costs and depot overhaul costs, was found. The optimum policy resulted in a 16 percent savings in initial inventory investment. Data was obtained from the Directorate of Propulsion and Auxiliary Power Systems, Headquarters, Air Force Logistics Command.

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A STUDY OF OPPORTUNISTIC REPLACEMENT TACTICS FOR MODULAR JET ENGINE MANAGEMENT

A Thesis

Presented to the Faculty of the School of Systems and Logistics

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the Requirements for the

Degrees of Master of Science in Logistics Management

and Master of Science in Facilities Management

By

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Captain Thomas J. Duvall

and

Captain Thomas J. Goetz

has been accepted by the undersigned on behalf of the faculty of the School of Systems and Logistics in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN LOGISTICS MANAGEMENT
(Captain Thomas J. Duvall)

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(Captain Thomas J. Goetz)

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COMMITTEE CHAIRMAN

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LIST OF ABBREVIATIONS

AEL Committee	Aerospace Engine Life Committee
AFIT	Air Force Institute of Technology
AFLC	Air Force Logistics Command
AFLC/LOP	Directorate of Propulsion and Auxiliary Power Systems, Headquarters, Air Force Logistics Command
COUHTA	Total Cost of Useful Hours Thrown Away
MOD-METRIC	Modified, Multi-Item, Multi-Echelon Multi-Indenture Inventory Model
MOT	Maximum Operating Hours
MTBD	Mean Time Between Demand
MTBF	Mean Time Between Failure
NRTS	Not Reparable This Station
OST	Order and Ship Time
TIN	Total Initial Inventory Investment (with opportunistic replacement)
$\overline{\text{TIN}}$	Total Initial Inventory Investment (without opportunistic replacement)
UHTA	Useful Hours Thrown Away

CHAPTER I

INTRODUCTION

Since 1959, the United States Air Force (USAF) has used actuarial techniques to predict engine failures (24:1-1). The actuarial technique is derived from principles used for life insurance mathematics, which, in turn, are based on the idea that probability of death increases as age increases. As applied to jet engines, for example, the actuarial technique presumes that fewer engines will survive to 1,000 operating hours than will survive to 500 operating hours. The actuarial technique is used to predict engine failures so that engine spare requirements and distribution and overhaul workloads can be determined (24:1-1). The actuarial technique does not directly address the cost of engine spares or overhaul workloads; it does not address cost reduction in Air Force jet engine management (24:1-1).

Despite the lack of cost considerations by the actuarial technique, there is an interest in minimizing the costs involved in jet engine maintenance (10). In this context, minimizing means achieving a given level of performance in jet engine maintenance for the least dollar amount. This interest in cost has been generated because engines are relatively more expensive today than ever before

and because resources required for engine maintenance are more scarce today than ever before (4:7).

The interest generated about jet engine maintenance has not gone unnoticed. A new engine design, the modular concept, has recently been developed for the Pratt and Whitney F-100 engine.[1] This design was originally developed to decrease engine repair time (9:11). Recently, however, interest has focused on exploiting the F-100 modular concept to minimize maintenance costs (9:5). There has been one research study directed toward the F-100 modular engine in particular (9). In addition, there have been at least three general models, aimed at minimizing maintenance costs, that could apply to jet engine maintenance in the Air Force (1; 19; 20). Finally, there is a body of knowledge concerning cost versus reliability principles (16:165). While much of this body of knowledge was developed by studying electronic equipment, the principles have application in the mechanical hardware area (26; 20:61).

Statement of the Problem

Despite the interest generated about jet engine maintenance costs and despite the existence of cost models

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[1]For a description of the modular F-100 engine see Chapter II, "Opportunistic Replacement for the F-100 Engine."

developed specifically for the F-100 modular engine, wholly integrated models which consider *all* cost aspects in a jet engine's life are apparently not in widespread use today. We formed this belief after we made the literature search and held interviews with the Directorate Chief and department heads of the Directorate of Propulsion and Auxiliary Power Systems, Air Force Logistics Command (AFLC/LOP).[2]

Justification

Attempts aimed at improving the efficiency of the Air Force jet engine management system are justified in view of high cost of the engines. For example, the projected FY 77 cost of the Pratt and Whitney F-100-PW-100 engine which powers the F-15 aircraft is 2.18 million dollars (4). If 750 of these engines were purchased to support the F-15 weapon system, the aggregate purchase price would be approximately 2.5 billion dollars. Since the purchase price alone is so substantial, any managerial improvement which would allow purchase of fewer engines without degrading the ability of the weapon system to do its job would be a boon to

---

[2]This search included the Defense Documentation Center (DDC), Defense Logistics Studies Information Exchange (DELSIE), the Air Force Institute of Technology (AFIT) faculty, and the AFIT Branch Air University Library including periodical literature, technical reports, and AFIT theses.

the taxpayer (as long as those savings exceed the cost of implementing the managerial improvement) (28:37).

One technique which could enable managers to reduce cost is modeling (12:367). If a system can be described by a model, then that model can be altered and "fine-tuned" in an attempt to find which management procedures facilitate cost reduction without incurring the expense of experimentation and disruption in the real world system (12:372). For example, a model of the engine management system for the F-100 jet engine could be analyzed in an attempt to find out what factors determine how many engines and what maintenance policies are required to support the F-15.

There have been at least three general areas of maintenance management for which cost models have been developed (1; 19; 20). In addition, one model directly addresses the F-100 engine which powers the F-15 aircraft. This model was developed by Forbes and Wyatt in 1975 (9). It is felt that this model could be useful in contributing to cost reduction of the F-100 management system. The Forbes and Wyatt model moves toward cost minimization by suggesting replacement of an unfailed engine module at an opportune time. For example, an opportune time could be when the engine is off the aircraft for another reason. This type of replacement policy is called an opportunistic replacement

policy. This policy can result in cost savings if the unfailed module is not replaced too frequently, that is, if it does not have a large amount of useful life remaining when it is replaced under the opportunistic replacement policy.

However, it is felt that the Forbes and Wyatt model offers only a partial step toward cost minimization. In order to present a more complete picture of the effects an opportunistic replacement policy has on a jet engine maintenance system, consideration must also be given to the impact that the policy has on engine and module spare inventory requirements. If too many extra spares are required to support this policy, then any cost savings due to opportunistic replacement may be offset by the additional cost of extra spares.

Objective

The objective of this research was to develop a model that can be used to help reduce costs of jet engine maintenance by utilizing an opportunistic replacement policy and relating that policy to spare engine and module inventory requirements.

Scope

This research is limited to the F-100 engine that powers the F-15 aircraft. This engine was chosen because

the Forbes and Wyatt model provides a great deal of background information upon which to build.

The F-100 engine is a new engine with approximately forty thousand total fleet hours (8). Because this engine is so new, there is little historical data collected for it. Consequently, such data factors as mean time between failure (MTBF) and mean time between demand (MTBD) can only be imprecisely estimated. The estimates used are those that are expected to reflect the state of the engine in 1981. A model developed from such estimated data is more likely to reflect the operational steady state of the F-100 engine.

Real world data was used to develop model parameters. We felt that perfectly accurate data were not required for this research, however, because this research effort is aimed at developing a model with provisions to update continually model parameters to reflect the "real world" operational steady state. Since the F-100 engine is still in its infancy, it is not the intent of this research to model the behavior of the F-100 engine in 1977, but rather to model the behavior of the F-100 engine when it reaches its operational steady state in 1981.

CHAPTER II

LITERATURE REVIEW

In order to accomplish the research objective, a variety of background information was required. First, generalized preventive maintenance and replacement maintenance models were studied. Second, maximum operating time concepts were reviewed. Third, the idea of opportunistic replacement was studied. Fourth, the Forbes and Wyatt model was studied. Fifth, the Air Force Mod-Metric model was studied to understand how spare inventory requirements can be related to engine behavior characteristics such as MTBF and MTBD.

The overall purpose of the literature review was to provide a background which, together with the research objective, enabled the development of research questions which are presented at the end of this chapter.

Theory of Maintenance

> The theory of maintenance falls under two divergent disciplines: capital theory (a topic in economics) and reliability theory (a topic in applied probability) [16:165].

Economic and stochastic factors in maintenance models account for this dual membership. The maintenance of equipment is first of all a special problem in the theory

of capital. The equipment produces output over its useful life. Amount of output, life length, and salvage value are all affected by maintenance. This general problem can be divided into two parts:

1. To determine when equipment should be replaced by new equipment.

2. To determine what maintenance actions should be taken during the life of the equipment.

It is the second problem which becomes heavily involved with reliability theory (16:166). The literature mentions two classes of stochastic models in conjunction with the second problem:

1. *Preparedness models--equipment* fails stochastically. Its actual state--good or bad--is not known.

2. Preventive maintenance models--equipment fails stochastically and its state--good or bad--is always known.

In the preventive maintenance model, if the equipment exhibits an increasing failure rate, and furthermore, if a failure during operation is more costly than replacement before failure, then it may be advantageous to replace the equipment before failure (16:166).[3]

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[3]The preventive maintenance model seems especially applicable to aircraft engines since engine operating condition is closer to being known than to not being known due to frequent inspections, test procedures, and operating environment.

Maintenance Model Development

Preventive Maintenance vs. Failure Maintenance

Reed has addressed the balance point between preventive maintenance costs and failure costs (20:60). The development of this balance point follows the assumption that preventive maintenance can reduce the number of failures and thereby avoid failure costs.[4] But as preventive maintenance efforts increase, associated costs can exceed the costs of equipment failure during operation. The task is to identify where the balance point is. That point identifies the minimum cost strategy. Figure 1 illustrates this concept.

> Note that although preventive maintenance may be added or deleted resulting in an approximately linear maintenance cost curve, the rate of reduction in failure costs drops rapidly and is asymptotic as preventive maintenance increases [16:61].

The cost of failure is given by:

$$F_C = p(F) \cdot C_F$$

where $p(F)$ is the probability of failure and C_F is the cost of failure if failure occurs. But both $p(F)$ and C_F are dependent on the level of preventive maintenance performed (P_{ML}), so that F_c now equals:

---

[4]Failure costs involve items such as component replacement, schedule disruption, downtime, and damage to other components.

$$F_c = \left(p(F) \cdot C_F\right) \Big| P_{ML}$$

This equation is then converted to two regression equations so that empirical data can be used to estimate the relationship between amount of preventive maintenance performed and probability of failure, and the relationship between amount of preventive maintenance performed and cost of a failure. The two regression equations are:

$$p(F) = a \cdot P_{ML}$$

$$C_F = b \cdot P_{ML}$$

where a and b are regression coefficients. By substituting, F_c becomes:

$$F_c = (a \cdot P_{ML}) \cdot (b \cdot P_{ML}) = a \cdot b \cdot P_{ML}^2$$

The minimum cost of the model occurs where equation $abP_{ML}^2 + cost/unit/effort \cdot P_{ML}$ is at a minimum (20:61).[5] It is important to note that preventive maintenance can range from simple greasing of bearings to periodic complete overhaul (20:60)

The Reed model is a generalized maintenance model which is designed to minimize costs. This idea may be

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[5]This point can be visualized using Figure 1. The total cost curve is the sum of the maintenance cost and failure cost curves.

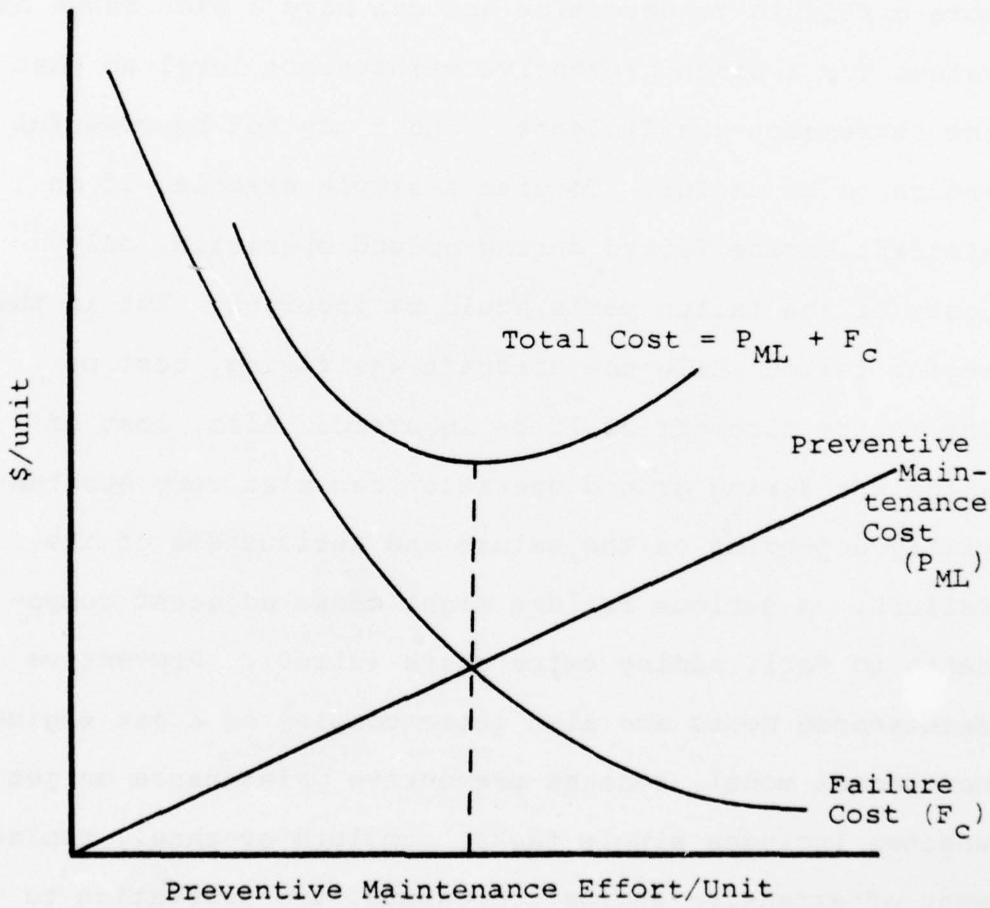

Fig. 1. Preventive Maintenance and Failure Maintenance Costs

incorporated into a total engine management system. However, it may be difficult to apply in a practical manner because certain difficulties must be overcome. For example, methods of computing accurate values for the variables need to be developed. The probability of failure could be estimated theoretically or empirically based on past experience. But failure costs are much more difficult to determine and can have a wide range of values for a given preventive maintenance level so that the regression coefficients a and b may not be powerful enough to be useful. To cite a simple example, if an aircraft engine failed during ground operation, only costs of the failed parts would be incurred. But if the engine failed while the aircraft was flying, cost of the entire aircraft could be incurred. Also, cost of a failure during ground operation can also vary substantially depending on the nature and seriousness of the failure. A serious failure might cause adjacent components to fail, adding extra costs (21:60). Preventive maintenance costs are also quite complex in a jet engine management model, because preventive maintenance on jet engines includes simple tasks, complete overhaul, replacement of expensive engine components, transportation to and from an overhaul facility, and engine removal and replacement.

A further refinement to the preventive maintenance concept considers replacement of unfailed components as a tactic of preventive maintenance. This consideration gives rise to the question: "Is there some policy of replacing unfailed engines which will save money?" The concept of maximum operating time can have an effect on the answer to this question.

Maximum Operating Time

The idea of maximum operating time (MOT) is important to the understanding of many maintenance policies, especially replacement of unfailed components. A piece of equipment must meet three conditions in order for it to be considered for an MOT (14:5). First, the failure rate must increase with the age of the item. Second, there must be a penalty associated with item failure during operation. Third, the benefits obtained from an MOT must exceed the costs involved in administering the MOT program. Engines satisfy these three conditions (14:5,6,7). Simply stated, an engine MOT is a specified number of operating hours. When the engine accrues this specified number of hours it is removed from the aircraft and overhauled (that is, its hours are "zeroed out"). Except for extraordinary situations, an engine is not operated in excess of its MOT.

MOTs are determined by the Aerospace Engine Life (AEL) Committee, a board of engine designers and logistic planners within AFLC (4). This committee determines MOTs by using a combination of technical and statistical methods. The technical method approaches the problem of MOTs by setting the MOT very low for a newly designed engine and observing how the engine behaves. As the engine nears its MOT, the engine is inspected. Some percentage of the fleet may be torn down and analyzed at this point. If no problems are discovered, the MOT is increased. If problems are encountered they will be corrected and the process repeated. As the engine again nears the new MOT, the engine is again inspected and evaluated. In this manner, the MOT is continually extended as the engine gains maturity and a historical record (14:10).

The statistical method approaches the problem of setting MOTs by analyzing the historical records of an engine and trying to predict when a future failure will occur. The MOT is set (ideally) just short of the predicted failure (14:11). In general, MOTs for new engines are set using the technical approach which gives way to the statistical approach after the engine has developed an historical record (8).

Until 1974, there was little concerted effort towards developing a systematic, quantitative approach

to setting MOTs (14:13). At that time the Air Force Logistics Command (AFLC) Operations Analysis Office began to search in earnest for a quantitative approach to determining MOTs. The Operations Analysis Office efforts resulted in a mathematical model.

> Basically the math model simply prices out alternative maximum time policies with the objective of finding the policy that produces the least total cost for some standard time period, such as the next 5 years [14:13].

While this mathematical model was not a panacea for setting MOTs for engines, it did provide a method of analysis and a point of reference for designers and planners. Ultimately, the AEL is responsible for determining MOTs (4).

Today, engine managers attempting to predict component wearout consider not only operating time, but also cycles (discussed below), and hours operated at maximum thrust (8:4). These three limiting factors are different in the way they track engine component wear. To illustrate, suppose that metal fatigue in a turbine blade occurs only when the blade is rapidly heated and cooled, as in rapid movement of the engine throttle from idle to full thrust and back to idle. If one uses only operating time as a limiting factor, one might lose the ability to track turbine blade wear, since operating time by itself gives no information about

how much strain the turbine blade has had. However, by tracking the number of times the throttle has been operated in the fashion explained above, we can much better predict the strain. This type of throttle movement is called a cycle, and there are many definitions of it. For example, a cycle could be defined to be an engine start and subsequent shutdown. Additionally, hours operated at maximum thrust is a way of tracking components which wear only at very high temperature (8), just as a cycle is a way of tracking components which wear only when rapid heating and cooling occurs. Stated another way, the wearout characteristics of the engine component determine the factor needed to track the component's pattern of use (8).

In order to establish a background for this research, it is important to mention a relationship between these three factors which sometimes permits the above factors to be interchanged in spite of their differences. If mission profiles (i.e., types of power settings, length of sorties, number of take offs and landings) remain similar for equal cycle limited parts on two different aircraft, those parts would both reach their cycle limits at the same time. In this case, an operating time limit (MOT) could be computed from the cycles per hour which occurred over the operating hours which have accrued. Under these conditions, such

an MOT is just as valid in tracking component wear as cycles are. In fact, past experience by AFLC/LOP seems to indicate that cycles can often be converted to MOT for management purposes in just such a fashion because flying units' mission profiles tend to be similar on the average (8).

The F-100 engine is not only a new engine but it also incorporates a new design, the module concept, which is discussed on page 21, Opportunistic Replacement for the F-100 Engine. For this reason, the MOT applies to each of five modules. That is, each module has its own unique MOT and is based on the most time limited part within the module (8).[6] The engine, composed of modules, does not require its own MOT (8). These MOTs have been developed by using the technical approach. The modules are each reaching their initial low MOTs and the inspections and subsequent resetting of MOTs is now taking place. For example, the core module initially had an MOT of 1,080 hours and now the AEL is considering moving the MOT to 2,160 hours (8). AFLC/LOP is moving toward a reduction in the number of engine modules and module parts required to have an MOT (8). This will be accomplished by a continuing process of reaching an MOT, inspecting some or all of the engines in the fleet, and extending

---

[6]That is, there are some parts within a module that have their own MOTs. These parts, then, are the determining factors in a module's MOT.

the MOT. By 1981, AFLC/LOP estimates that all modules will have MOTs between one-thousand and five-thousand hours (8).

Planned Replacement

Barlow and Proschan have addressed the replacement decision in a paper entitled, "Planned Replacement."

> If the unit is characterized by a failure rate that increases with age, it is wise to replace it before it has aged too greatly. On the other hand, one cannot plan too frequent replacements without incurring excessive costs. Thus, there exists the problem of specifying a replacement policy that balances the cost of failures against the cost of planned replacements [1:63].[7]

The objective function is developed as follows: Suppose that a unit operating continuously over time $(0,t)$ is replaced upon failure. Replacement may also occur before failure if desired. A cost c_1 includes all costs associated with replacement of a failed unit. A cost $c_2<c_1$ includes all costs incurred for each nonfailed item that is replaced. If $N_1(t)$ denotes actual number of failures in $(0,t)$ and $N_2(t)$ denotes the number of replacements of nonfailed items in $(0,t)$, then the expected cost is:

$$C(t) = c_1 \cdot E\left(N_1(t)\right) + c_2 \cdot E\left(N_2(t)\right)$$

[7]Failure rate is the number of equipment failures per specified time period. Hazard rate is the same thing.

where $E(N(t))$ is the expected number of each N. An optimal replacement policy is one which minimizes $C(t)$. A "strictly periodic" policy is then developed by which a unit is replaced at some exact number of hours, h, after its installation; or at failure, whichever occurs first. Hours, h, is held constant, once it is determined which h gives minimum expected cost, over time interval $(0,t)$. That minimum is then compared to the cost of scheduling no planned replacements in $(0,t)$. If optimal planned replacement cost is less than no planned replacement cost, then following a policy of planned replacement with replacement interval h minimizes expected costs. Otherwise, the optimal policy is to replace only at failure (1:64).

To reiterate, this model calculates a miminum expected cost strictly periodic replacement policy, whose elements include those of failed and unfailed units. The resultant cost under the optimal replacement policy is compared to the expected cost of a replacement at failure-only policy, and the lower cost becomes the optimal solution to the problem (1:65).

The planned replacement model introduces the concept of replacing unfailed, but aging parts, before they fail and cause failure costs to be incurred. It adds the dimension of a replacement strategy which can be used to help identify preventive maintenance costs.

However, the difficulties of identifying costs of failure and costs of replacing unfailed equipment were not addressed in the Barlow model. Finally, the planned replacement model specified fixed periodic replacement for one component only. The next model to be discussed introduces the idea of convenience and timing in replacement maintenance policies as a further means of optimizing costs.

Opportunistic Replacement

The opportunistic replacement model as developed by Radner and Jorgenson relates not only to the replacement of unfailed parts, but also to the *timing* of replacement of unfailed parts.

> Replacement policies are of interest if the cost of replacement after failure is greater than the cost of replacement before failure. For example, consider the act of replacing all lamps in a street lighting system. The cost per lamp of replacing all lamps at once is much less than the cost of replacing each lamp as it fails. The cost of additional lamps must be balanced against the cost of additional failures that occur if replacement is postponed [19:185].

Suppose now there is a piece of equipment composed of *two* modules. If one of the modules fails, the failed module must be replaced. If the cost of replacing the second unfailed module at the same time as the failed module is less than the cost of replacing the second module upon failure, it is efficient to do so (19:186).

Opportunistic replacement is another refinement of replacement policy designed to optimize maintenance costs. It represents a further contribution to the determination of preventive maintenance costs. The next model to be discussed applies the ideas of opportunistic replacement to the development of a model which pertains directly to the F-100 engine management system.

Opportunistic Replacement for the F-100 Engine

Another model that was developed to optimize cost is directly related to the F-100 engine. This model was developed by an AFIT research team, James Forbes and Phillip Wyatt (9). The stated objective of their research was to locate the economical replace, not replace break-points for the modules of the Pratt and Whitney F-100 engine. The F-100 engine is composed of five modules which, when bolted together, comprise the entire engine as shown in Figure 2.[8] Each module has a specified MOT. The central question of their research was: If the engine is removed from the aircraft to repair a known malfunctioning module, can a policy be developed to determine if an adjacent nonfailed, but high-time, module nearing its MOT should also be replaced (9:5,21)?

[8]There are engine accessories outside the five modules but these were excluded from consideration.

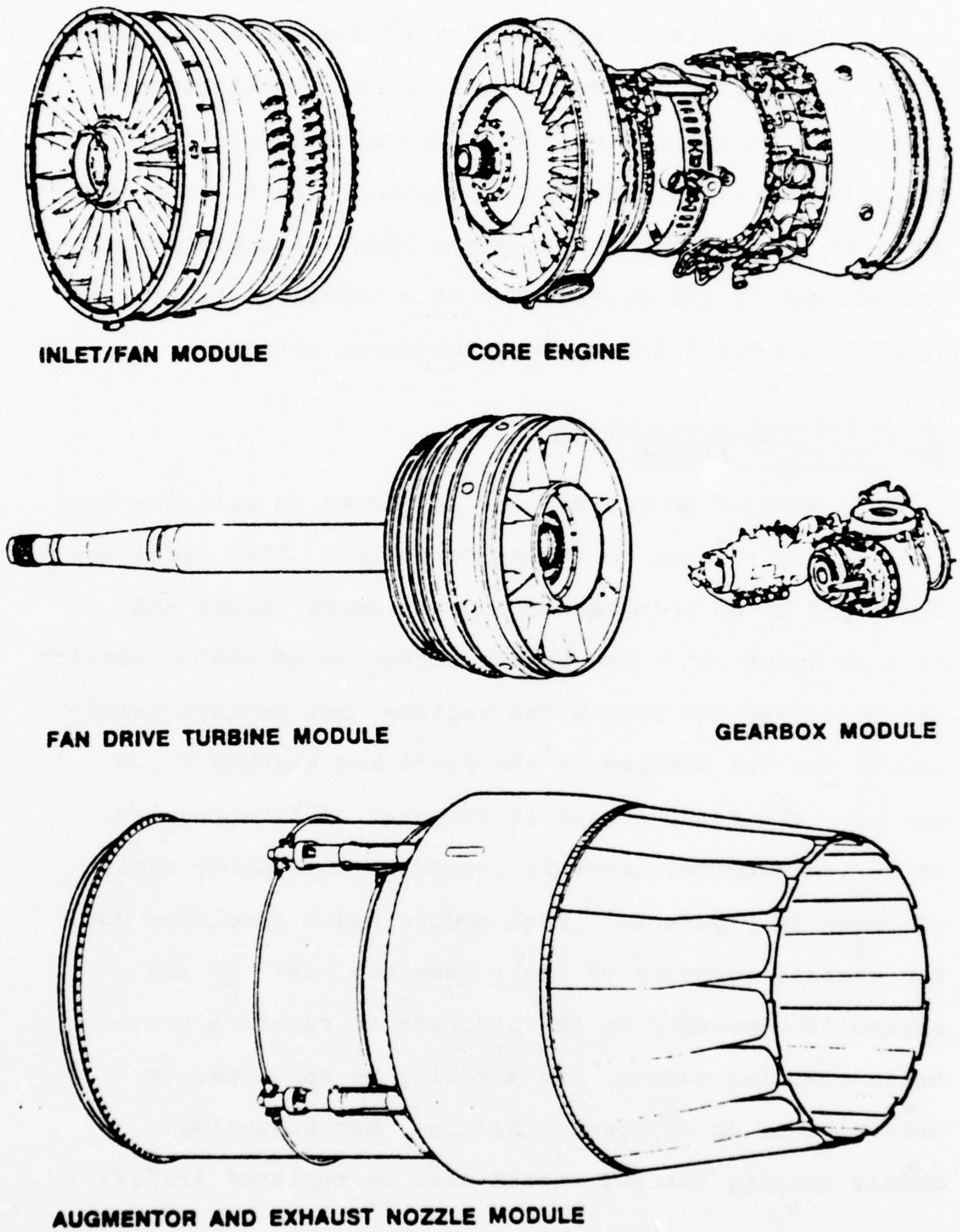

Fig. 2. F-100 Engine Modules (9:2)

If this opportunity to replace such a high-time module is passed up, engine removal and teardown costs would again be incurred upon the eventual failure of the module or upon the arrival of the module MOT. If the opportunity to replace the high-time module were not passed up, the subsequent removal and teardown costs could be avoided. Forbes and Wyatt made it clear that there is a penalty for replacing a nonfailed module. If the unfailed module is replaced too soon, so much of the removed module's remaining life will be discarded that the subsequent engine removal and teardown costs saved will not offset the cost penalty.

The model developed by Forbes and Wyatt determines the optimal replacement policy for an unfailed module by relying on two major concepts. First, an unfailed module can only be opportunistically replaced if the module exhibits an increasing hazard rate; and second, the cost to replace an unfailed module at a given opportunity is less than the additional cost of replacing that module after it has failed (9:13). The model divides the life of a module into two regions as shown by Figure 3. N hours is equivalent to module MOT. If there is an opportunity to replace an unfailed module which has accrued operating hours between 0 and n hours the module is not replaced. If there is an opportunity to replace an unfailed module which has accrued operating

hours between n and N hours, however, the module is replaced. The point defined by n is the economical replace not replace breakpoint for the F-100 modules. These breakpoints minimize the engine operating costs per hour. The position of the breakpoint, n, is dependent on the hazard rate parameter of the module. The breakpoint is also dependent upon the overhaul cost of the module, the cost of engine removal, and the cost of the amount of useful life remaining on the module (9:37).

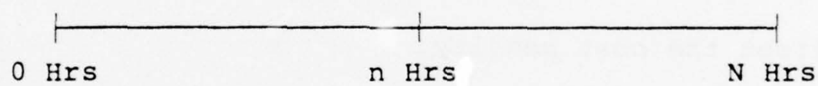

Fig. 3. Module Life Cycle

The first key concept, an increasing hazard rate, is especially critical to the model for the following reasons (16:171). If the hazard rate was not increasing, it could only be constant or decreasing. A constant hazard rate means that module age does not affect the likelihood of module failure. In other words, a new, low-time module is just as likely to fail as an old, high-time module. Therefore, replacement of an unfailed module with a new low-time module would not reduce the chance of failure. The only advantage of opportunistic replacement under a constant hazard rate is forestalling

the removal of a module due to MOT arrival and subsequent mandatory replacement.

If, on the other hand, the hazard rate was decreasing, an old high-time module would be less likely to fail than a new low-time module and replacement of an unfailed module would never be beneficial.

The Forbes and Wyatt model has two major limitations.

The first limitation was the method of determining the relative differences in costs of replacing a module before it fails and replacing it after it fails. Three factors influence this difference (9:17). First, there are differences in the amount of downtime required to replace a failed versus nonfailed module. Second, there are differences in the amount of resources required to replace a failed versus nonfailed module. Third, opportunistic replacement makes use of the "sunk" costs of engine removal and teardown which are required anyway to repair the known malfunction.[9] Only the third factor was entered into the model because it was the only factor that could be obtained. The researchers were confident that if the other two factors were added

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[9]The costs are "sunk" because they are incurred in order to return the engine to a serviceable condition not to replace an unfailed module. As such, they are incurred whether or not the opportunity is taken to replace an unfailed module.

to the model, more precise results would be obtained and thus their model is felt to be conservative (9:19).

The second limitation was that the model did not consider the effect that opportunistic replacement might have on spare engine or spare module inventory requirements (9:77). That is, the model did not address the following question: Does an opportunistic replacement policy require that more spare engines and/or modules be purchased to support the same level of performance that existed prior to the opportunistic replacement policy?

Inventory Requirements for Spare F-100 Engines

One tool which the Air Force utilizes for management of spare modular engines is a program called MOD-METRIC (Modified Multi-Item, Multi-Echelon, Multi-Indenture Inventory Model).[10] The program is a computerized mathematical inventory model designed to specify the optimal number of engines and modules to buy and where to store them in order to provide the fewest backorders for a given dollar investment. Since MOD-METRIC was used as an integral part of this research, it is necessary to discuss how it works.

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[10]This program was developed by AFLC/LOP for use on the Honeywell 6000 computer, CREATE, at AFLC.

In this model, a particular engine or module may be demanded at any of several bases; in turn, these locations are resupplied from a central depot (17:3).

> The maintenance concept is to remove an engine which has failed, replace that engine with a serviceable one, determine the module (or modules) containing the defective part (parts), remove that module from the failed engine, and replace it with a like module from serviceable stock. Depending on the type of failure, the module will be repaired either at the base or at depot level [17:3].

The concept capitalizes on the engine's modular construction to keep whole engines out of repair for longer periods of time. Whole engines are returned to serviceable condition through module replacement, and the number of days per year that a spare engine will be in a serviceable condition is substantially increased (17:4). Figure 4 shows a diagram of MOD-METRIC's maintenance and inventory concept.

There are two concepts which are important to understanding MOD-METRIC. First, in the vocabulary of inventory theory, the MOD-METRIC model can be described as an $(s-1,s)$ inventory policy, that is, when one item is demanded (fails), another is ordered to replace it. This statement means that the quantity of spare assets at base level remains constant over time, where stock on hand plus on order from the depot minus backorders equals spare assets (17:9). Second, in the vocabulary of

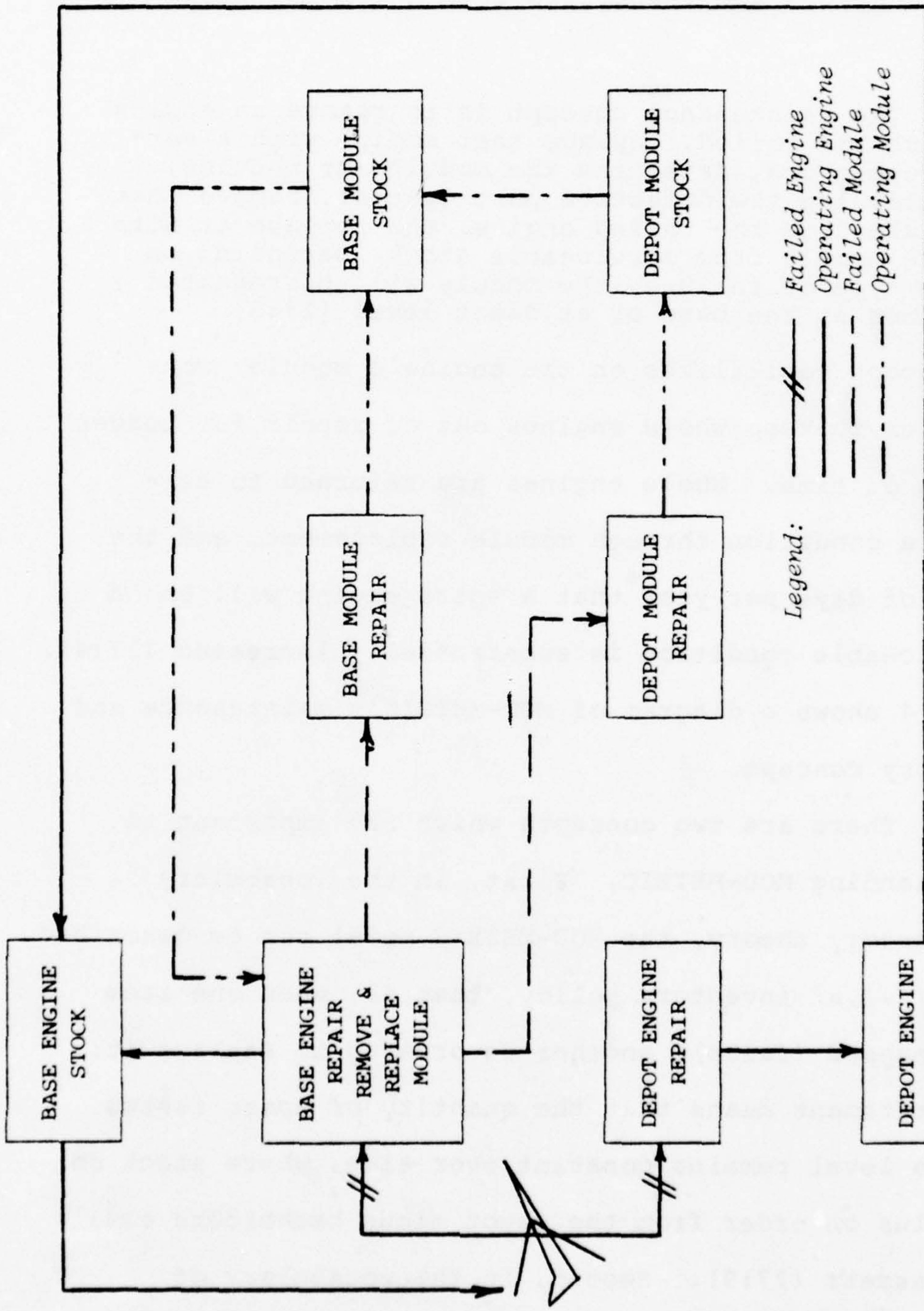

Fig. 4. Modular Repair Concept (14:5)

queuing theory, this model can be described as possessing an infinite number of servers, because the customer arrivals (engine failures) never have to wait to be served. As soon as the engine fails, it is served, that is, the repair cycle begins. The reason why this idea is important becomes apparent in the following discussion.

The performance measure of MOD-METRIC is expected base engine backorders (a backorder occurs when an engine is needed at a particular base and the base does not have a serviceable spare in stock). Various data must be input to the model. They include average base and depot repair times for each item, unit costs, percentage of items repaired at depot instead of base, and average order and ship times. Additionally, the demand process must be specified.

The next step is to determine how these various data impact expected base engine backorders. Initially, only one base and only whole engines are discussed for purposes of clarity. Later in the discussion, modules are incorporated into the model.

Let λ = Daily demand rate

r = Percentage of engines repaired at the base

R_B = Base repair time (total time an engine is repairable when it is repaired at the base)

R_0 = Order and ship time (OST)(total time between when an item becomes repairable and when a serviceable replacement is received from the depot; includes delay incurred if the depot happens to be out of serviceable stock)

T = Average resupply time (the time between when an item becomes repairable and when base supply is furnished with a serviceable replacement.

The average resupply time *(T)* is an overall measure which directly affects the number of expected backorders, and is expressed in terms of the previously defined variables as follows:

$$T = r(R_B)+(1-r)R_0$$

T is analogus to an average service time in queueing theory. Since the system behaves as an infinite server system, and demands occur in a Poisson fashion with mean λ, the number of units in resupply can be shown to be Poisson distributed with mean λT (17:6), where:

$$P(\text{no. repairables}=X) = \frac{e^{-\lambda T}(\lambda T)^X}{X!}$$

The MOD-METRIC performance measure, expected backorders, can then be calculated by first observing that backorders

can occur only if *X*, the number of repairables, exceeds *s*, the stock level of spares. Then:

$$\text{Expected backorders} = B(s) = \sum_{X=s+1}^{\infty} (X-s) \cdot P(X|\lambda T)$$

By expanding this expected backorder calculation to include all bases instead of just one, and by allowing the *s* and *T* values to vary for each base, the computer program utilizes marginal analysis to calculate optimum stock levels at each base. These optimum stock levels obtain the least number of backorders per dollar of investment (17:19). The objective function and dollar constraint for such an overall program appears as follows:

$$\text{Minimize} \sum_{i=1}^{M} \sum_{X=s_i+1}^{\infty} (X_i - s_i) \cdot P(X_i|\lambda_i T_i)$$

subject to:

$$\sum_{i=0}^{M} c \cdot s_i \leq B$$

where: i = Base i

c = Cost

B = Budget

The MOD-METRIC program adds another dimension to this objective function, a dimension which takes into account the fact that a module is a subassembly of an engine rather than a separate component with the same importance as a whole engine. If this dimension were not included in the program, the program would dictate purchase of many modules (which are cheaper than whole engines) and few engines. This specification occurs because by buying modules under the simple model thus far developed, the least number of backorders per investment dollar can be achieved by purchasing many cheap items and few expensive ones. Yet the object of MOD-METRIC is to minimize engine backorders, not to minimize overall engine and module backorders. An adjustment in the program is necessary to assure that whole engines are given proper emphasis. The modules are subordinated to the engines in importance by manipulating the constraint, as shown:

$$\text{Minimize} \sum_{i=1}^{M} \sum_{x_i=s_i+1}^{\infty} (X_i - s_i) \cdot p(X_i | \lambda_i T_i)$$

Subject to:

$$\sum_{i=1}^{M} \left(c_e s_i + \sum_{j=1}^{N} c_j s_{ij} \right) + \sum_{j=1}^{N} c_j s_{0j} + c_e s_0 \leq B$$

where:

B = Budget

C_j = Cost of module j

j = Module j

c_e = Cost of whole engine

s_{0j} = Stock level of module at depot

s_0 = Stock level of engines at depot

In solving this modified problem, a partitioning technique must be used. MOD-METRIC incorporates this technique and computes the number of engines and modules to buy and where to store them in order to get the greatest reduction in engine backorders per investment dollar. The procedure that MOD-METRIC uses to solve the problem with this constraint is complex, and an explanation of it is beyond the scope of this research. For a more detailed discussion of the partitioning technique, see John A. Muckstadt and John M. Pearson, "MOD-METRIC, A Multi-Item, Multi-Echelon, Multi-Indenture Inventory Model" (17).

Research Questions

Based upon the research objectives and the literature review, we developed the following research questions:

1. What impact does an opportunistic replacement policy have on spare engine and module inventory investment?

2. What effect does *varying* the opportunistic replacement policy have on the spare engine and module inventory investment?

3. Can the opportunistic replacement policy be varied to achieve a minimum of total costs due to inventory and discarded module life?

CHAPTER III

METHODOLOGY

This chapter describes how the research questions were answered. First, we discuss the method of determining the impact of opportunistic replacement on spare engine and module inventory requirements. Next, we address the method of determining the effect of varying the opportunistic replacement policy on spare engine and module inventory requirements. Finally, we discuss the question of determining a minimum of total cost due to inventory and thrown away module life.

Finding the Impact of Opportunistic Replacement on Spare Engine and Module Total Initial Inventory Investments

We used a two-step procedure to evaluate the impact of opportunistic replacement on spare investment. In the first step, we used a simulation to determine demands for the engine and its modules for various opportunistic replacement policies. In the next step, we used the MOD-METRIC program to determine the dollar investment required to maintain a given performance level for each of those various opportunistic replacement policies. However, before detailed discussion

proceeds, it is necessary to provide background for the reader on why the first research question was answered in this two-step fashion.

It is well known that if demands for an item change, then inventory levels required to provide a given support criterion may also change (11:472). Therefore, a study of the impact of opportunistic replacement on spares inventory investment implies the need to study module and engine demands under different opportunistic replacement policies.

There are two basic approaches to studying the difference of these demands. One way involves the inductive process, where empirical data was used to generalize to an overall situation (7). For example, by using empirical demand rates under different opportunistic replacement policies, statements can be made about the general underlying characteristics of the demand distribution. The other way involves a deductive process where generalized real world information is used to describe a set of data. For example, by using a known or estimated parameter of a real world distribution of demands, predictions can be made about what magnitude each demand will have.

Since opportunistic replacement is not currently practiced on the F-100 engine (13), the empirical data needed to generalize about demand differences

is not available. Therefore, the deductive process must be used.

One powerful method of studying demand differences by a deductive process is simulation. Simulation can be used as a deductive tool because it can take general information such as average time between failures and convert it to number of demands over some specific set of operating parameters. These parameters can be any set of operating conditions which the simulation designer wants to include. Simulation also has other advantages. Its concepts are easy to grasp, and the operating parameters are easy to manipulate for sensitivity analysis. It can model situations which are too complex to describe by a rigorous mathematical model. The demand processes for the model used in this research are complex because random, unscheduled module failures introduce different combinations of remaining module lives for each engine. A mathematical description of such a model quickly becomes impractical. Also, simulation can often provide predictive information from within its structure that is hidden, or not recoverable in empirical data (11:621). Since a deductive process had to be employed, and since this research benefits from the above advantages, simulation was the tool which we chose to study the magnitude of different demands for engines and modules under different opportunistic replacement policies.

After we decided how to determine demands for different opportunistic replacement policies, we needed a method to determine how much inventory is required for each opportunistic replacement policy. We chose the AFLC/LOP MOD-METRIC program to perform this task for three major reasons. First, we felt that some credible method should be employed. MOD-METRIC was thought to be credible because it is currently being used as a tool with which to project operational inventory requirements of F-100 jet engines (8; 13). Second, MOD-METRIC was specifically designed for repairable items where subassemblies (modules) impact the performance of the complete assembly (engines) but are of lesser importance precisely because they are subassemblies. The F-100 jet engine with its modules fits nicely into this category The third reason is that the program was available to us for our study and experimentation at Wright-Patterson Air Force Base.

With this background in mind, the reader is nearly ready to consider the details of the methodology. First, however, a more specific technical concept of opportunistic replacement must be introduced. Up to this point, the idea of opportunistic replacement was discussed in general terms, but a more precise definition is needed. We first defined a variable PERC that can range from a value of zero to one. The variable PERC defines the opportunistic replacement

policy by defining a point in the interval of zero hours to MOT hours. If PERC equals .5, for example, then this point is equal to .5×MOT hours. The significance of that point is: If an opportunity exists to replace an unfailed module, look at the accrued operating hours on the module. If the accrued hours are less than .5×MOT do not replace the unfailed module. Otherwise, replace the unfailed module. This PERC variable is referenced frequently in the discussion which follows.

Step 1: Simulation

The simulation models a set of F-100 engine module failures over a given flying hour program and produces information relating to the number of failed engines and modules (for both scheduled and unscheduled replacements). Required inputs to the simulation include estimates of MTBF for each module, estimates of MOT for each module, the opportunistic replacement policy (that is, PERC) for each module, and the length of the flying hour program. Given those inputs, the simulation draws a time to failure for each module and considers the shortest time to failure as the first opportunity to replace any of the other unfailed modules. It opportunistically replaces a module if time left to mandatory replacement is within the opportunistic replacement specification for that module. The simulation then increments a set of counters and draws new times to

failure for each newly installed module. It then repeats the process, beginning with choice of the shortest time to failure. The simulation terminates when the flying hour program is completed. Actual output includes MTBD[11] for the engine and for each module, total number of useful hours thrown away for each module (UHTA), the total present value of hours thrown away for each module, and the percentage of modules returned to the depot for repair instead of being repaired at the base. Five areas bear further discussion.

First Area. This simulation assumes that times to failure for the modules are exponentially distributed, which means that the failure rate for each module remains constant (22:71). This arrangement does not seem consistent with earlier statements by Forbes and Wyatt that the hazard rate must be rising for replacement before failure to be cost effective. However, imbedded in the constant hazard assumption which we made for the simulation is the assumption that the AEL Committee has properly identified operating limits for parts within a module. This proper identification precludes the module

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[11]MTBD is the average time between demands for three types of module replacement: those which failed unexpectedly, reached their MOT, or were opportunistically replaced. MTBF is the average time between demands for the unexpected failures only.

from exhibiting a significantly rising hazard rate before module parts have reached their operating limits. In addition, experience indicates that the hazard rate for complex pieces of equipment with many interacting parts such as in engine modules rises very slowly between zero and maximum operating hours. It rises so slowly that a constant hazard provides a reasonable approximation of the actual hazard (15). Consequently, we employed a constant hazard for this research.

Second Area. The percentage of modules returned to the depot for repair instead of being repaired at the base is called the *Not Reparable This Station* (NRTS) rate. When a module is removed due to failure it is sent to the base level repair shop or the depot for repair (see Figure 4). If the module is sent to the base repair shop, the module is repaired and considered serviceable. The module is not returned to zero hours however (3). When the module comes out of base level repair, it still retains the same number of accrued operating hours it had when it failed. But when a module is sent to the depot for repair, the module is overhauled and is considered to have zero hours on it (zeroed out) when it is returned to a serviceable condition (3). When a module is removed from an engine

because it has reached its MOT, the module *must*[12] be sent to depot where it is overhauled and its hours are zeroed out. Only the depot can zero out a module's hours. When a module is opportunistically replaced, it is still in a useable condition. Therefore, the base level repair shop does not need to do any work on it. Indeed, even if the base repair shop *did* work on the opportunistically replaced unfailed module, nothing would be gained because the module would still retain the operating hours it had accrued up to the time it was opportunistically replaced. On the other hand, the module could be sent to the depot and be overhauled and have its accrued operating hours returned to zero.

For the purposes of this research, we are limiting the handling of opportunistically replaced modules to the latter case (sending the opportunistically replaced modules to depot). The reason for this is that reusing a module without zeroing out its accrued operating hours introduces complexities beyond the scope of this research. For example, an entire policy must be developed to determine how well the operating time remaining on the reused module must match the operating time left on all the

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[12] This is because the base cannot zero out hours and hence the module cannot be used until the depot overhauls it. See Section II, MOT section.

other modules comprising an engine into which the reused module is to be installed. By sending all opportunistically replaced modules to the depot for repair, the NRTS rates for the modules are altered and this change must be accounted for in the simulation for the following reasons. First, if NRTS increases, the number of engines sent to depot for repair increases. This increased number tends to increase average resupply time,[13] which in turn alters performance of the overall inventory system. Second, NRTS is one of the input variables to the MOD-METRIC program. For these two reasons, the simulation includes a feature which calculates the effect of opportunistic replacement on the NRTS rate, and adjusts it accordingly.

For this research we assumed that all opportunistically replaced modules are returned to the depot for overhaul. Therefore, an opportunistic replacement policy may significantly increase the depot workload because the NRTS rate increases. In order to be sure that the MOD-METRIC program receives a correct NRTS rate input, the simulation calculates an adjusted NRTS rate for each module as follows:

1. We tracked the total number of actually failed modules and of opportunistically replaced modules.

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[13]See p. 30.

2. We multiplied the number of actually failed modules by the nonopportunistic replacement NRTS rate.

3. Next, we added the number of opportunistically replaced modules to the result in Step 2. This sum represents the total number of modules sent to the depot.

4. Finally, we divided this sum by the total number of modules that were replaced due to either actual failure or opportunistic replacement. This quotient is the adjusted NRTS rate.

The above procedure is repeated for each of the modules and for each simulation/MOD-METRIC run.

Third Area. *In real life*, when an unfailed component is replaced, no one knows with certainty how many actual hours of useful life are thrown away. No one knows because the item could fail unexpectedly between the time of opportunity and the maximum operating time. If this event occurs, then less hours were thrown away than if the component had worked right up to its MOT. However, the simulation overcomes this error because it always has a current time-to-failure value stored for each module. Thus, when opportunistic replacement occurs, the simulation has the exact amount of UHTA. This feature allows the simulation to give more meaningful (i.e., not overstated) amounts of UHTA.

Fourth Area. It is important to discuss the method we used to determine the cost of a single hour of module life.[14] Recall that all opportunistically replaced modules are assumed to be sent to the depot for repair and that the depot zeros out the module operating hours.[15] The cost of an hour of module life of an opportunistically replaced unfailed module can be directly related to the cost required to return that module to zero hours (3). This cost can consist of many factors (9:56). Each cost of transportation, packaging, manpower, and depot repair costs can be considered. However, by observing the relative magnitude of these costs, we found that the estimated depot overhaul cost for the modules ranged from sixteen to two-hundred times greater than all the other costs associated with module overhaul (9:85; 6:2).

In addition, the depot overhaul costs that we obtained for this research are the costs that are currently being used by AFLC/LOP for planning purposes and computing reimbursements (6). For these reasons, we decided to use only the depot overhaul costs in computing the cost of a single hour of thrown away module life.

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[14]The term "module life" in this context refers to just the MOT of a module. A module is a repairable item and consequently can be repaired and reused many times. Therefore, a module's overall life cycle can be many times greater than its MOT.

[15]See p. 42.

The cost of an hour of module life is related to depot overhaul cost by simply dividing the cost to overhaul a module by the module's MOT.

Fifth Area. The final discussion is the method we used to find the present dollar value of the total useful hours thrown away for all modules. We employed standard concepts of discounting and the DOD-approved interest rate of 10 percent per annum. In order for the simulation to handle discounting, the 10 percent interest rate was converted by a two-step process to a rate more amenable for calculation of discounted value of engine flying hours thrown away. First, the simulation converts the yearly flying program from units of one hour to units of fifty hours.[16] Thus, a flying hour program of 48,000 hours per year (i.e., 48,000-hour units per year) becomes 48,000÷50=960 fifty-hour blocks per year. Second, the simulation converts the 10 percent rate mentioned previously to an interest rate per fifty hours (called PINT in the simulation). After these two steps, the simulation

[16]We discounted in fifty-hour blocks rather than one-hour blocks because we could not get timely simulation results on the CREATE computer at Wright-Patterson Air Force Base, when units of less than fifty hours were used. Under other circumstances, one-hour units could be used.

calculates discounted value of a fifty-hour block of life thrown away as follows:

1. $$\text{PINT} = \frac{\text{10\% Interest Rate}}{\text{Annual Flying Program in 50-Hour Units}}$$

2. $$\text{Cost per Hour} = \frac{\text{Cost of Depot Overhaul}}{\text{MOT}}$$

3. Present Value of 50 Hours Thrown Away =

$$\frac{\text{50 Hours} \times \text{Cost per Hour}}{(1 + \text{PINT})^{n}}$$

where n is the number of fifty-hour blocks that have accrued in the simulation up to the point in time where the fifty-hour block being thrown away is located. If one-hundred hours are being thrown away, then total discounted value of those one-hundred hours is computed as follows:

1. Compute discounted value of the first fifty hours by the procedure shown above.

2. Increment n by one.

3. Repeat Step 1 for the second fifty hours.

4. Add the results of Steps 1 and 3. This sum gives the cost of useful hours thrown away for each module. The simulation sums these costs for all modules and outputs a total cost of useful hours thrown away (COUHTA).

The flowchart and FORTRAN IV computer program for the complete simulation are in Appendixes A and B. The simulation just discussed provides information that is required for the MOD-METRIC program, which is discussed next.

Step 2: MOD-METRIC

The MOD-METRIC program was used to determine the impact of opportunistic replacement on spare engine and module inventory requirements. The inputs for MOD-METRIC are (25:3-1):

1. The number of bases utilizing the F-100 engine powered F-15 aircraft.

2. The number of flying hours per month at each base.

3. The OST for each base in days. OST represents the average total number of days required to secure a serviceable engine or module from depot for use at base level.

4. The cost of the engine and each of the five modules.

5. The MTBD for the engine and each module.

6. The percentage of engines and modules returned to the depot for repair instead of being repaired at the base (NRTS).

7. The time required for base and depot repair for the engine and each module.

The CARDIN input program that was used to call up the MOD-METRIC program is shown in Appendix C. This CARDIN input program is compatible with the Honeywell 6000 CREATE computer located at AFLC Headquarters, Wright-Patterson Air Force Base, Ohio. In addition to the CARDIN input program, two special files were also used to input the data to the MOD-METRIC program. These two files, "BASES1" and "RUN___" were called up by the CARDIN program for entry into the MOD-METRIC program. BASES1 contains the number of bases, the OST, and the flying hour program. RUN___ contains the rest of the information. The BASES1 file is shown in Appendix D. A typical RUN___ file, RUN 801, is shown in Appendix E. In addition, there are several parameter inputs required to control the program, and these are fully explained in an Air Force Logistics pamphlet entitled, "Recoverable Inventory Control Using MOD-METRIC" (25).

The MOD-METRIC program output is a graph of the relationship between the total initial inventory investment (TIN) cost (this consists of spare engines and modules) and the expected number of backorders. The expected number of backorders is the measure of jet engine maintenance performance that was held constant throughout this research. This measure was held constant in order to study the effect of opportunistic replacement on TIN cost and UHTA costs. The performance measure

chosen was one backorder because this is related to an 80 percent ready rate. The 80 percent ready rate is that required by Department of Defense Instruction (DODI) 4230.4 for combat and combat support aircraft (27). The ready rate can be described as the probability of having enough spares to meet demands, or alternatively, as the probability that there is *not* an aircraft out of commission because no serviceable engine is available. Using the same notation that was used to introduce MOD-METRIC, the ready rate is given as:[17]

$$\sum_{x=0}^{s} P(x|\lambda T)$$

By using a marginal approach, the relationship between ready rate and expected backorders can be shown. It will be recalled that expected backorders is given by:

$$B(s) = \sum_{x=s+1}^{\infty} (x-s)\cdot p(x|\lambda T)$$

Then

$$B(s+1)-B(s) = -\sum_{x=s+1}^{\infty} p(x|\lambda T) = \sum_{x=0}^{s} p(x|\lambda T)-1$$

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[17]See p. 31.

Although ready rate and expected backorders are related as shown above, MOD-METRIC uses backorders in calculating spares requirements because weight is given not only to occurrence of backorders but also to number and length of occurrences (18).

Since in this research backorders were held constant at one, the MOD-METRIC output can be considered to be a single value, TIN costs. We define the MOD-METRIC output in this manner in order to simplify discussions about MOD-METRIC output. Thus, TIN costs become the dependent variable of the MOD-METRIC program.

The independent variables in the MOD-METRIC program are those seven variables listed on page 48. Since this research is only concerned with the changes in TIN costs and UHTA costs that are caused by opportunistic replacement, only the MOD-METRIC input independent variables which are effected by opportunistic replacement were studied. That is, throughout this research we kept the number of bases, the flying hour program, the OST for each base, the initial purchase cost for engines and modules, and the base and depot repair time constant. We allowed only the MTBDs and NRTS rates to vary. Note that these two variables are the *dependent* variables (outputs) of the simulation but are the *independent* variables (inputs) for the

MOD-METRIC program. That is, the simulation "feeds" the MOD-METRIC program.

In order to determine the impact of opportunistic replacement on TIN, the following procedure was used:

1. Run the simulation using no opportunistic replacement: PERC=0.

2. Use the MTBDs and NRTS rates from the simulation for inputs to the MOD-METRIC program.

3. Obtain total initial investment with no opportunistic replacement ($\overline{\text{TIN}}$).

4. Repeat Steps 1 and 2, using opportunistic replacement ($0 \leq \text{PERC} \leq 1$).

5. Obtain TIN.

6. Compare TIN with $\overline{\text{TIN}}$ to determine the impact opportunistic replacement has on spare engine and module inventory investment.

This procedure is summarized in Figure 5.

Varying Opportunistic Replacement Policies

After the impact of opportunistic replacement on TIN costs was explored we turned our attention to determining the effect of *varying* opportunistic replacement on TIN costs. We developed two methods of varying the opportunistic replacement on TIN costs. The reader may want to review the discussion concerning the variable PERC

and its relationship to opportunistic replacement at this time. First, we needed to develop these methods in order to limit to a reasonable task the number of combinations of modules and PERCs to compare. For example, if PERC was varied in .1 increments from zero to one (i.e., PERC could take on eleven values), then the PERCs of the five modules could be combined in 11^5 ways which equals 161,051 combinations. The sheer magnitude of such a large number of comparisons makes a complete enumeration of all combinations impractical. Second, we needed to develop some method of ordering the PERCs so the relationship between PERC values and TIN costs could be visualized in two dimensional space. Therefore, the following methods were developed to enable us to make the comparisons between the module PERC combination within the time available for this research.

The first method of varying the opportunistic replacement policy was simply to keep all module PERC values equal to each other and vary the PERC value in unison from zero to one in .1 increments. Recall that these values of PERC are inputs to the simulation along with module MTBF, module MOT, and total flying hours for the life of the system to yield an MTBD for the engine and modules.[18] These MTBDs are then fed into the

[18]Recall further that the simulation does not require an MTBF input for the engine itself because the

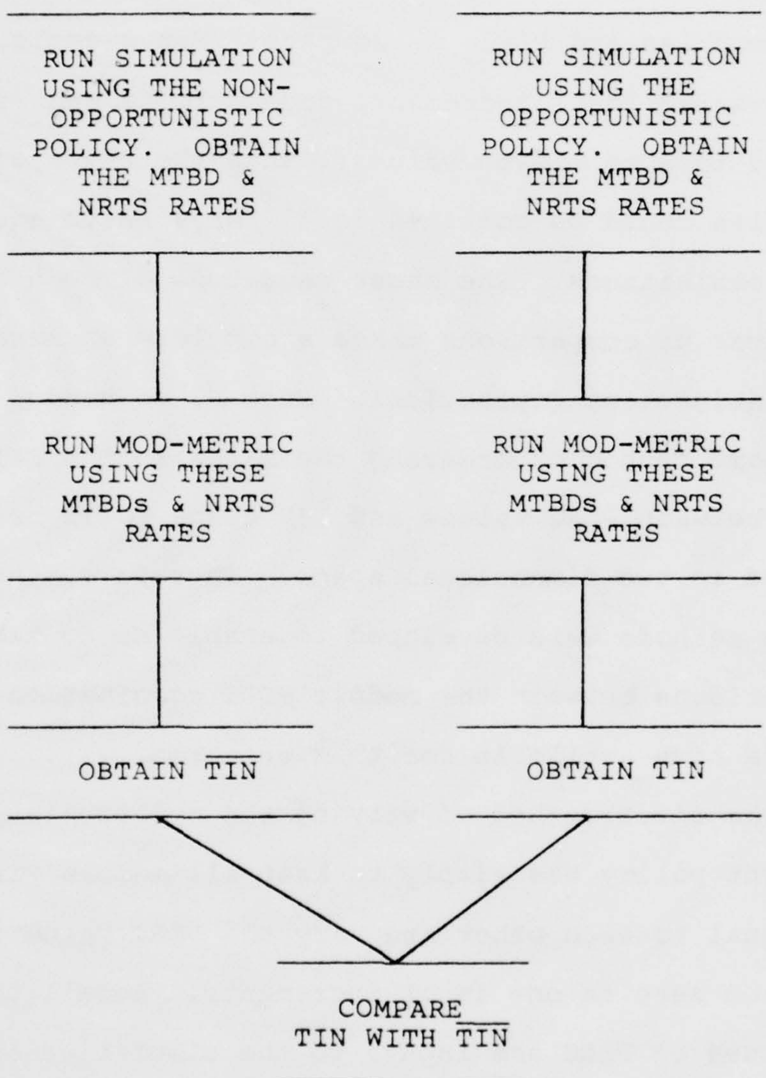

Fig. 5. Algorithm for Comparing TIN with $\overline{\text{TIN}}$

MOD-METRIC program to determine TIN costs. Note that when PERC=0 (i.e., no opportunistic replacement), then TIN is really $\overline{\text{TIN}}$. As PERC was varied then, we were able to see how TIN varied. Figure 6 illustrates this algorithm. We utilized the graph shown in Figure 7 to present a picture of the PERC vs. TIN relationship.

The second method of varying the opportunistic replacement policy was to weight the value of PERC according to the MTBF of the module. For example, a module with a high MTBF would be given a low value of PERC. This tactic seems attractive because one would be throwing away comparatively less useful life of a module with a high MTBF. The scheme developed for determining these PERCs is as follows. We started all modules at PERC =0. Then we increased the module with the lowest MTBF by .1 from 0 to 1.0. This PERC is called the base PERC in the remainder of this research. We increased the other modules based on the following increments:

$$\frac{\text{MTBF of Module with Lowest MTBF}}{\text{MTBF of Module in Question}} \times .1$$

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simulation calculates the engine MTBD directly from the other simulation inputs.

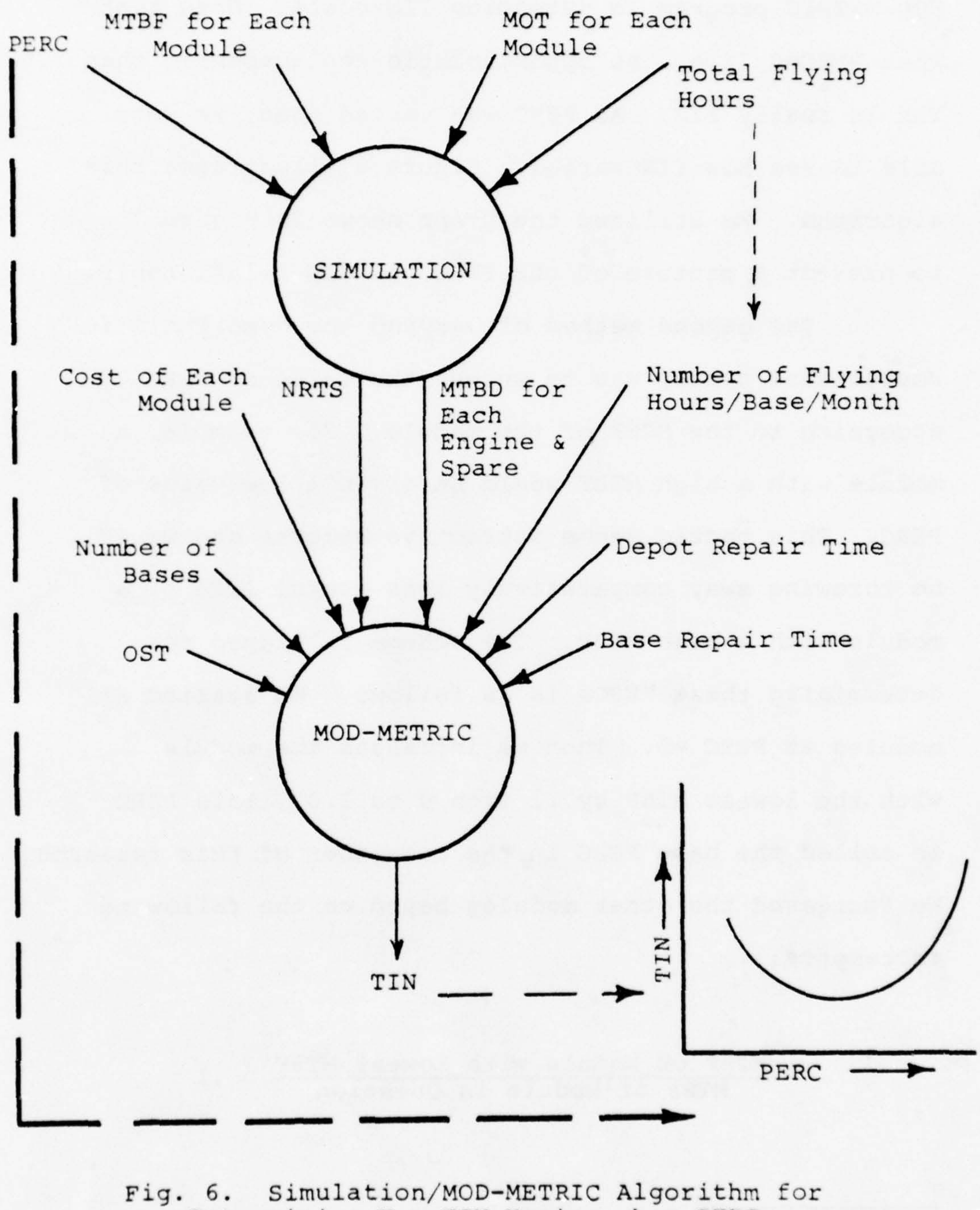

Fig. 6. Simulation/MOD-METRIC Algorithm for Determining How TIN Varies when PERC is Varied

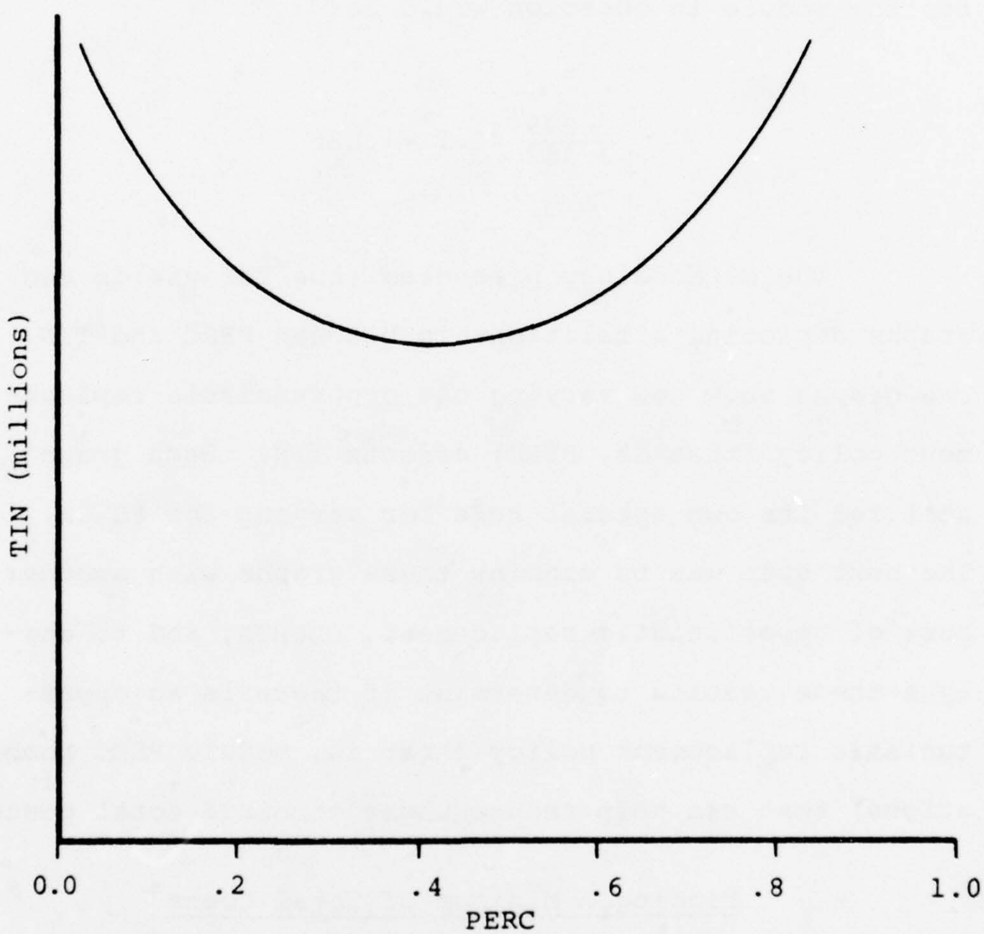

Fig. 7. Typical PERC vs. TIN Relationship

For example, suppose the module with the lowest MTBF had an MTBF of 1,999 hours and the module in question had an MTBF of 2,352 hours. The increment for the module with the lowest MTBF would be .1 and the increment for the module in question would be:

$$\frac{1,999}{2,352} \times .1 = .085$$

The methodology presented thus far yields two graphs depicting a relationship between PERC and TIN. The graphs show how varying the opportunistic replacement policy (that is, PERC) affects TIN. Each graph utilized its own special rule for varying the PERCs. The next step was to combine these graphs with another cost of opportunistic replacement, COUHTA, and to analyze these results to determine if there is an opportunistic replacement policy (that is, module PERC combinations) that can help reduce these combined total costs.

Finding A Minimum of Total Costs

In order to find the minimum of the combination of the TIN costs and COUHTA, the TIN costs and COUHTA are simply added together. The result is a total cost. This total cost can be plotted against PERC (for Method 1) and base PERC (for Method 2). These graphs will look

similar to the graph in Figure 7 but the vertical axes will be total cost instead of TIN costs.

Assumptions and Limitations

The following assumptions and limitations were made throughout this research and are reviewed here for the reader's convenience.

1. Only the F-100 engine which powers the F-15 aircraft was studied. This limitation allowed us to make the assumption of similar mission profiles on the average for all the engines with greater confidence than would be possible if we included all aircraft using the F-100 engine.

2. Only the modules of the F-100 engine were considered. That is, the engine accessories were excluded from this research. Inclusion of the engine accessories outside the modules was beyond the scope of this research, since they would complicate the simulation and the MOD-METRIC algorithm. We felt there would not be enough time to complete our research if accessories were included in the problem.

3. Only two bases, each with a constant flying hour program and similar mission profiles, were used.

4. We allowed only the MTBD and NRTS rate to vary when opportunistic replacement was used. The

performance level was held constant at one expected backorder.

5. Engine and module purchase costs were held constant.

6. Depot overhaul cost for each module was held constant.

7. The engine was not considered to be replaced opportunistically and consequently underwent no change in NRTS rate.

8. There were no overhaul costs associated with the engine as a unit. Overhaul costs were attributed to the modules only.

9. Order and ship time for the bases as well as the base and depot repair times were held constant. This limitation requires a brief discussion. Allowing the order and ship times to vary simultaneously with the NRTS rate was beyond the scope of this research, but the effect of opportunistic replacement on order and ship times eventually has to be considered. To illustrate this effect, recall that the average resupply time T is given as:[19]

$$T = r(R_B) + (1-r)R_0$$

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[19]See p. 30.

We allowed $(1-r)$, the NRTS rate, to increase as opportunistic replacement increased, but held R_0, order and ship time, constant. A rising NRTS rate increases T, but so does a rising R_0. If both NRTS and R_0 are allowed to rise as opportunistic replacement increases, the resulting increase in T is more pronounced than if only NRTS is allowed to increase. Recall that order and ship time includes delay incurred if the depot happens to be out of serviceable stock. This delay might increase as opportunistic replacement increases, due to increased work backlogs, or a host of other capacity factors which were beyond the scope of this research. Nevertheless, the variable R_0 is clearly related to workload of the depot, and must be allowed to vary with opportunistic replacement if depot workload is to be wholly included in this opportunistic replacement model.

10. One of the assumptions of MOD-METRIC is that only one module fails at any given time. That is, when the engine is removed from the aircraft to repair a failed module, there is only *one* failed module (17:24). Consequently, the supply system need only provide a single module replacement for each engine removal. An opportunistic replacement policy can result in more than one module being replaced, however: The module that fails plus any module(s) that is opportunistically replaced. We believe that violation of the MOD-METRIC assumption

(single module failures only) would have no significant impact on the MOD-METRIC output for opportunistic replacement. Our assumption is based on the following discussion of repair time as it pertains to MOD-METRIC.

Let B_i = Average base engine repair time at base i.

R_i = Average engine repair time at base i if a module is available.

Δ_i = Average delay in engine repair time at base i if modules are not available.

Therefore

$$B_i = R_i + \Delta_i \tag{17:24}$$

Opportunistic replacement increases Δ_i above what Δ_i would be for nonopportunistic replacement because by opportunistic replacement we are, in effect, increasing the number of module demands and therefore increasing the probability that a particular module will not be available when needed.

In order to precisely calculate Δ_i under opportunistic replacement, modules must be treated as failing independently, and also as failing jointly with all other modules (one failure and one opportunistic replacement for example). For the F-100 engine, the joint probabilities of two to five "failures" (that is, actual failures as well as opportunistic replacements) must be

computed for each module. One approach is to determine the conditional probability: Given an actual module failure, what is the probability that each of the other modules will require opportunistic replacement? This probability is clearly a function of the opportunistic policy, that is, the PERC values for each module. There are five conditional probabilities for a five module engine. These probabilities could be determined empirically from the simulation results. The MOD-METRIC program could then be modified to use this probability information to compute new values of Δ_i. We found that the value of Δ_i was very small compared with the value of R_i (Δ_i values are a by-product of the MOD-METRIC output available to the user by special request) (25:3-1). The impact on Δ_i by an opportunistic replacement policy was felt to be small (5). Consequently, we felt that the total effect of opportunistic replacement, through Δ_i, on B_i was small enough to be disregarded. We therefore made this assumption throughout the remainder of this research.

CHAPTER IV

DATA COLLECTION

The objective of this research was to develop a model that can be used to help reduce the cost of jet engine maintenance. We feel that it is important to develop the F-100 engine opportunistic replacement policy to reflect the steady-state engine characteristics when the engine has reached maturity. At the present time, the F-100 engine is still considered to be a new engine and many of its operating characteristics like MTBF are still changing because of the wear-in process (4; 8). Consequently, we selected 1981, five years from when the F-15 became operational as the time frame for which the model would be developed. There is nothing profound about the five years of operation other than the fact that the F-100 engine fleet will have accrued about one-million flight hours and should be well past any wear-in period of operation.[20]

We arbitrarily set the total life of the weapon system and the F-100 engine at ten years. We felt that

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[20]A mature engine fleet is one that has accrued about one million operating hours (5). The actual flying hour program is classified but one-million operating hours in five years is a reasonable estimate based on other similar flying programs (5).

this time span allowed ample time for the simulation to stabilize and run without using up too much computer time.

Since the flying hour program is classified, we assumed a flying hour program of two-thousand hours per base per month. This is a reasonable estimate based on similar aircraft and missions (8). We chose to use a two-base system, which is similar to current operational reality. This yields a total system flying hour program of 480,000 hours: 2 bases × 2,000 hours/month/base × 12 months/year × 10 years. The AFLC/LOP set the OSTs at twelve days for Base 1 and nine days for Base 2 for planning purposes. The twelve-day OST value simulates an overseas base (8).

The MTBF estimate for the engine and for each of the modules was obtained from AFLC/LOP by use of a "per rate factor." We obtained the per rate factor, which is the number of unscheduled removals (that is, failures) per one-thousand hours of operation, from a letter which was written to Headquarters, Aeronautical Systems Division from Pratt and Whitney Aircraft, Division of United Aircraft Corporation (P&W). A copy of this letter was forwarded to AFLC/LOP for their use. The letter says that for a mature engine fleet, their estimate for this

factor is 2.5 (23:4).[21] It must be stated that the per rate factor is only an estimate, developed from actual data collected on existing similar types of jet engines. However, its general accuracy has recently been reinforced through a simulation which Pratt and Whitney performed using the most recent failure data on the F-100 engine (8). The F-100 engine is expected to reach its mature state of one-million operational hours in 1981 (8). Consequently, we used this factor to develop the MTBF for the engine and the modules. These MTBFs are developed easily in the following manner.

The engine itself does not really fail. A component within a module fails, which causes the module to "fail," which causes the engine to "fail." Each module contributes a certain percentage of the engine failure per one-thousand hours factor according to a letter to AFLC/LOP from the F-15 Systems Project Office (2:3). These percentages are listed in Table 1 in the row labeled "Percent Contribution." Note that the percentages do not add up to 100 percent because the engine

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[21]AFLC/LOP considers an engine fleet to be mature when the engine fleet has accrued one-million operating hours (8). One-million operating hours was selected because experience with other jet engines shows that the individual engine per rate levels off and remains nearly constant after the engine fleet accrues one-million operating hours. The engine fleet is considered to have reached steady-state after one-million operating hours.

TABLE 1

SIMULATION AND MOD-METRIC INPUT DATA SUMMARY

	Engine	Core	Fan	Turbine	Aug-mentor	Gear Box
Percent Contribution	. . . . .	20	17	5	15	3
Per Rate (Failures per 1,000 Hours)	2.500	.500	.425	.125	.375	.075
MTBF (Hours)	400	2,352	1,999	8,000	2,667	13,332
Initial Purchase Costs ($)	2,180,000	919,900	231,000	220,100	470,800	30,500
Depot Overhaul Costs ($)	N/A	101,483	27,402	32,858	41,000	4,225
Depot Repair Time (Days)	42	37	25	21	24	18
Base Repair Time (Days)	6	8	4	5	4	3
MOT (Hours)	N/A	2,160	3,600	1,920	20,000	1,000
NRTS Rate (%)	10	29	30	30	13	33

accessories, which are not included in this analysis, can also contribute to engine failure.[22] The engine failure per one-thousand hours factor was multiplied by these percentages to get a module failure (which caused the engine to fail) per one-thousand hours factor. These factors are also displayed in Table 1 in the row labeled "Per Rate." Note that the engine per rate is also displayed. To convert the per rates to MTBFs, simply invert the per rates. The MTBFs thus obtained are in terms of hours. Example: Per Rate = 2.5 removals/1,000 hours.

$$\text{MTBF} = \frac{1}{2.5\left(\frac{\text{Removals}}{1000\ \text{Hrs}}\right)} = \frac{1000\ \text{Hrs}}{2.5\ \text{removals}} = \frac{400\ \text{Hrs}}{\text{Removal}}$$

The four-hundred hours represents hours between removals or MTBF. This conversion was carried out for each module and the results are contained in Table 1 in the row labeled "MTBF."

The initial purchase cost of the engine and each module are also summarized in Table 1. These cost figures were obtained from AFLC/LOP and represent the planning costs currently being used by AFLC.

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[22]See p. 59.

The depot overhaul costs for each of the modules are summarized in Table 1. These costs are current as of 1 January 1977 and were obtained from AFLC/LOP (6:8).

The depot and base repair times for the engine and for each module were obtained from AFLC/LOP and are the values used by AFLC in day-to-day planning (8). This data is summarized in Table 1.

The module MOTs used in this research have been the subject of much controversy since, practically speaking, the F-100 module MOTs may never be "determined with certainty" (4). The best guess that AFLC/LOP could make about the MOTs by the 1981 time frame was that they would all range between one-thousand and five-thousand hours (8). One of the problems in determining what MOTs should be used is that MOTs are actually based on three factors.[23] However, the cycle factor can be converted to operating hours *given that the mission profile is the same.* This may seem to be a gross assumption at first. But, since there are a large number of engines in the fleet (approximately 450), the effect of different mission profiles tends to average out (8). AFLC/LOP frequently makes this "averaging out" assumption for management purposes and converts cycles to operating hours by multiplying cycles by a factor of 1.2 (8). By

[23]See p. 15.

using this information, we developed the MOTs in Table 1. The core module is presently limited[24] to 900 cycles or:

$$900 \times 1.2 = 1,080$$

operating hours. This limit will probably be adjusted to 2,160 hours by the end of 1977 (8). Consequently, we used a core module MOT of 2,160. The gearbox module was recently assigned an MOT of one-thousand operating hours due to an internal bearing (5). The fan and turbine modules have cycle limits of 3,000 and 1,600 cycles respectively. The cycle information for the fan and turbine was retrieved from the G337 tracking system designed for the F-100 engine at Tinker Air Force Base, Oklahoma. The G337 system tracks the engines and modules and serialized components within modules along with the cycles and operating hours they have accrued. These cycle limits equate (using the 1.2 factor) to 3,600 and 1,920 operating hours respectively. Since there is no indication that these limits will be changed soon, we used them as they were. The augmentor has no cycle or operating hour limits (8; 4; 5). That is, it is inspected and, if found serviceable, it is not replaced regardless of the number of hours it has accrued. Consequently,

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[24]Recall that a *module* is limited only in so far as its most time limited internal part.

in order to allow the simulation to work, the MOT for the augmentor was set arbitrarily high to 20,000 hours. In addition, the augmentor PERC value was always set to zero. These two simulation input parameters insure that this module failed prior to reaching its MOT and that it was never opportunistically replaced. The MOTs are summarized in Table 1.

It is important to note that the MOTs selected are not based on a definitive policy. The trend is to eliminate operating limits of all types as much as possible (8). But, for the foreseeable future, some kind of operating limit will be utilized for at least a few components in the F-100 engine to avoid failures during flight operations (8).

The NRTS rates for each module and for the engine are summarized in Table 1. These are the currently used NRTS rates and they were supplied by Headquarters AFSC, in a letter to AFLC/LOP (2).

CHAPTER V

ANALYSIS

We first ran the simulation program using the data shown in Table 2, Simulation 1, and a flying hour program of 48,000 hours per year. Note that the opportunistic replacement policy, represented by the PERC values all equaling zero, was to *not replace opportunistically*. The results of the simulation, that is, the MTBDs and NRTS rates for the engine and each of the modules, are also displayed in Table 2. We then ran the MOD-METRIC program using the input data (see Figure 6) that is displayed in Table 3, MOD-METRIC Run 1. The MOD-METRIC program resulted in a total initial inventory investment (TIN) of $39,047,729 for an expected backorder value of one.

We next reran the simulation, Simulation 2, using PERC values of .5 for each module. This is equivalent to an opportunistic replacement policy which states: "When there is an opportunity to replace a module and that module has 50 percent or less of its useful life remaining to MOT, replace the module; otherwise, do not replace the module." Recall that the augmentor module and the gearbox module are never opportunistically

TABLE 2

SIMULATION 1

	Engine	Core	Fan	Turbine	Aug-mentor	Gear Box
Inputs						
PERC (%)	N/A	0	0	0	0	0
MTBF (hours)	N/A	2,352	1,999	8,000	2,667	13,332
MOT (hours)	N/A	2,160	3,600	1,920	20,000	1,000
Results						
MTBD (hours)	300	1,348	1,575	1,756	2,719	970
NRTS	.10	.29	.30	.30	.13	.33

COUHTA = $0.0

TABLE 3

MOD-METRIC RUN 1

	Engine	Core	Fan	Turbine	Aug-mentor	Gear Box
Inputs						
Initial Purchase Cost (4)	2,180,000	919,900	231,000	220,100	470,800	30,500
MTBD (hours)	300	1,348	1,575	1,756	2,719	970
NRTS	.10	.29	.30	.30	.13	.33
Depot Repair Time (days)	42	37	25	21	24	18
Base Repair Time (days)	6	8	4	5	4	3
Number of Bases: 2	Base 1	Base 2				
OST (days)	12	9				
Flying Hour Program (hours/month)	2,000	2,000				
Results						
TIN Costs: $39,047,729						

replaced and thus their PERC values remain equal to zero. All other input data for Simulation 2 remained the same as it was for Simulation 1. The inputs to and results of this simulation are displayed in Table 4, Simulation 2. Finally, we reran the MOD-METRIC program using the data from Table 5, MOD-METRIC Run 2. Note that the input data in Table 5 is the same as the input data in Table 3 except the MTBDs for the engine and modules and the NRTS rates for the modules. In Table 3 the MTBDs and NRTS rates are generated from Simulation 1 in which all PERC values equalled zero. In Table 5, the MTBDs and NRTS rates are generated from Simulation 2 in which the PERC values equal .5 for the modules that are opportunistically replaced. Therefore, the results of the two MOD-METRIC runs are different only because the input MTBDs and NRTS rates are different (as a result of different PERC values input into the two simulations). TIN costs of the second MOD-METRIC run were $35,956,702 for an expected backorder value of one.

Thus, we have shown that an opportunistic replacement policy (represented by PERC=.5) does have an impact on the total initial inventory investment costs in the MOD-METRIC program.

At this time, we direct the reader's attention to a comparison of the results of Simulations 1 and 2.

TABLE 4

SIMULATION 2

	Engine	Core	Fan	Turbine	Aug-mentor	Gear Box
			Inputs			
PERC	N/A	.5	.5	.5	0	.5
MTBF	N/A	2,352	1,999	8,000	2,667	13,332
MOT	N/A	2,160	3,600	1,920	20,000	1,000
			Results			
MTBD	503	1,191	1,310	1,164	2,875	828
NRTS	.10	.66	.53	.93	.13	.64

COUHTA = $7,203,660

TABLE 5

MOD-METRIC RUN 2

	Engine	Core	Fan	Turbine	Aug-mentor	Gear Box
Initial Purchase Cost (4)	2,180,000	919,900	231,000	220,100	470,800	30,500
MTBD	503	1,191	1,310	1,164	2,875	828
NRTS	.10	.66	.53	.93	.13	.64
Depot Repair Time	42	37	25	21	24	18
Base Repair Time	6	8	4	5	4	3

Number of Bases: 2	Base 1	Base 2
OST (days)	12	9
Flying Hours per Month	2,000	2,000

Results

TIN Costs: $35,956,702

Notice that the MTBD for the engine increases. That is, the *demand* for the engine decreases. Conversely, the MTBDs for the core, fan, and turbine, decrease. That is, *demand* for these items increase. These results are intuitively attractive. One expects fewer engine demands, because fewer module MOTs are reached. The augmentor module comparison should not be made since this module is not opportunistically replaced and does not have a practical MOT.[25]

We also direct the reader's attention to a comparison of MOD-METRIC Runs 1 and 2. The MOD-METRIC program calculates the number of engines and modules the purchaser should buy in order to achieve the TIN costs. Notice that in Run 2, the MOD-METRIC program appears to be purchasing fewer high initial purchase cost items (engines) at the expense of more low initial purchase cost items.

After finding that it is possible for opportunistic replacement to have an impact on TIN costs, we proceeded to determine the effect that varying the opportunistic replacement policy had on TIN costs. The two methods of varying PERC were applied and several combinations of PERC were explored.[26] These combinations

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[25]The difference in augmentor MTBD between MOD-METRIC Runs 1 and 2 is due to random fluctuation in the simulation.

[26]The reader may wish to review p. 53.

are shown in Table 6, Method 1, and Table 7, Method 2, under column heading "PERC." The PERC value increments are shown at the bottom of each table. For each of the PERC combinations, a simulation was run to generate the engine and module MTBDs. The set of MTBDs corresponding to one combination of PERCs was then input into the MOD-METRIC program. It is important to note that (1) all of the input data for all of the simulations (except PERC values) remained constant, and (2) all of the input data for all of the MOD-METRIC runs except MTBDs and NRTS rates (obtained from the corresponding simulation) remained constant. The end results of the MOD-METRIC runs (TIN costs) are shown in Tables 6 and 7 under column headings "TIN Costs."

Next, we drew a graph for each of the two methods of varying PERC. PERC values (base PERC for Method 2) were plotted against TIN costs. These graphs are shown in Figures 8 and 9. The graphs corresponding to each method of varying PERC values were observed to have the following property: They are convex. That is, as PERC is increased from zero to one, TIN costs decrease at first and then increase. There *appears* to be a region where TIN reaches a minimum.

While this property seems obvious and straightforward, the observer must be aware that if PERC were only incremented by .1 and *all* possible PERC combinations

TABLE 6

METHOD 1

PERC Combinations					TIN COSTS	COUHTA	TOTAL COST
Core	Fan	Tur-bine	Aug-mentor	Gear Box			
0	0	0	0	0	$39,047,729	$ 0	$ 39,047,729
.1	.1	.1	0	.1	35,665,880	507,810	36,018,861
.2	.2	.2	0	.2	36,050,557	1,507,810	37,558,367
.3	.3	.3	0	.3	35,358,145	2,723,230	38,081,375
.4	.4	.4	0	.4	35,199,944	4,575,859	39,775,803
.5	.5	.5	0	.5	35,956,702	7,203,660	43,160,362
.6	.6	.6	0	.6	39,747,848	12,285,909	52,033,757
.7	.7	.7	0	.7	43,711,046	17,255,073	60,966,119
.8	.8	.8	0	.8	45,719,124	23,438,828	69,157,952
.9	.9	.9	0	.9	50,611,223	31,390,693	82,001,916
1.0	1.0	1.0	0	1.0	58,165,728	44,824,366	102,990,094
.1	*.1*	*.1*	*0*	*.1*	*Increments*		

TABLE 7

METHOD 2

PERC Combinations					TIN COSTS	COUHTA	TOTAL COST
Core	Fan	Tur- bine	Aug- mentor	Gear Box			
0	0	0	0	0	$39,047,729	$ 0	$39,047,729
.085	0	.025	0	.015	38,474,493	271,154	38,745,647
.170	.2	.050	0	.030			
.255	.3	.075	0	.045	38,551,631	1,571,324	40,122,955
.340	.4	.100	0	.060	39,104,282	2,539,031	41,643,313
.425	.5	.125	0	.075	40,088,912	4,758,146	44,758,146
.510	.6	.150	0	.090	40,703,908	6,008,158	46,712,066
.595	.7	.175	0	.105	44,022,253	11,032,988	55,055,241
.680	.8	.200	0	.120	46,676,637	14,033,662	60,710,299
.765	.9	.225	0	.135	48,579,567	18,271,230	66,850,797
.850	1.0	.250	0	.150	54,173,689	27,739,333	81,913,002
[illegible]	.1	*.025*	*0*	*.015*	*Increments*		

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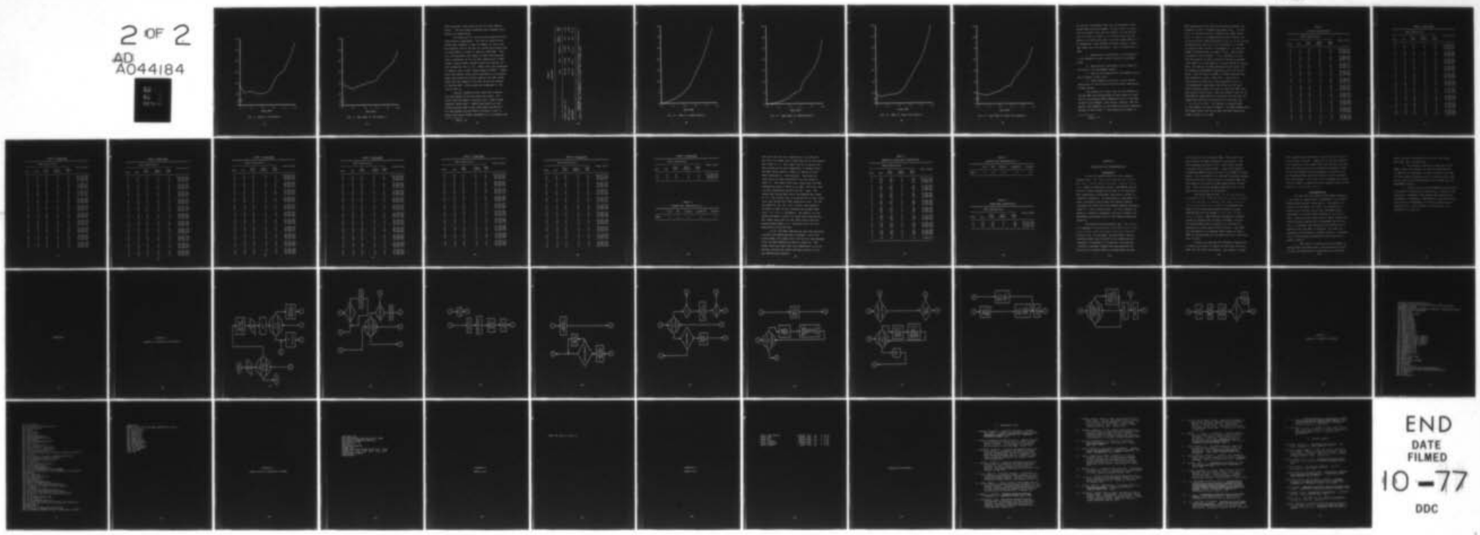

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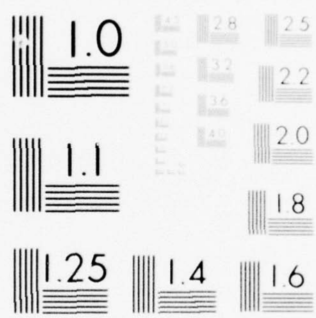

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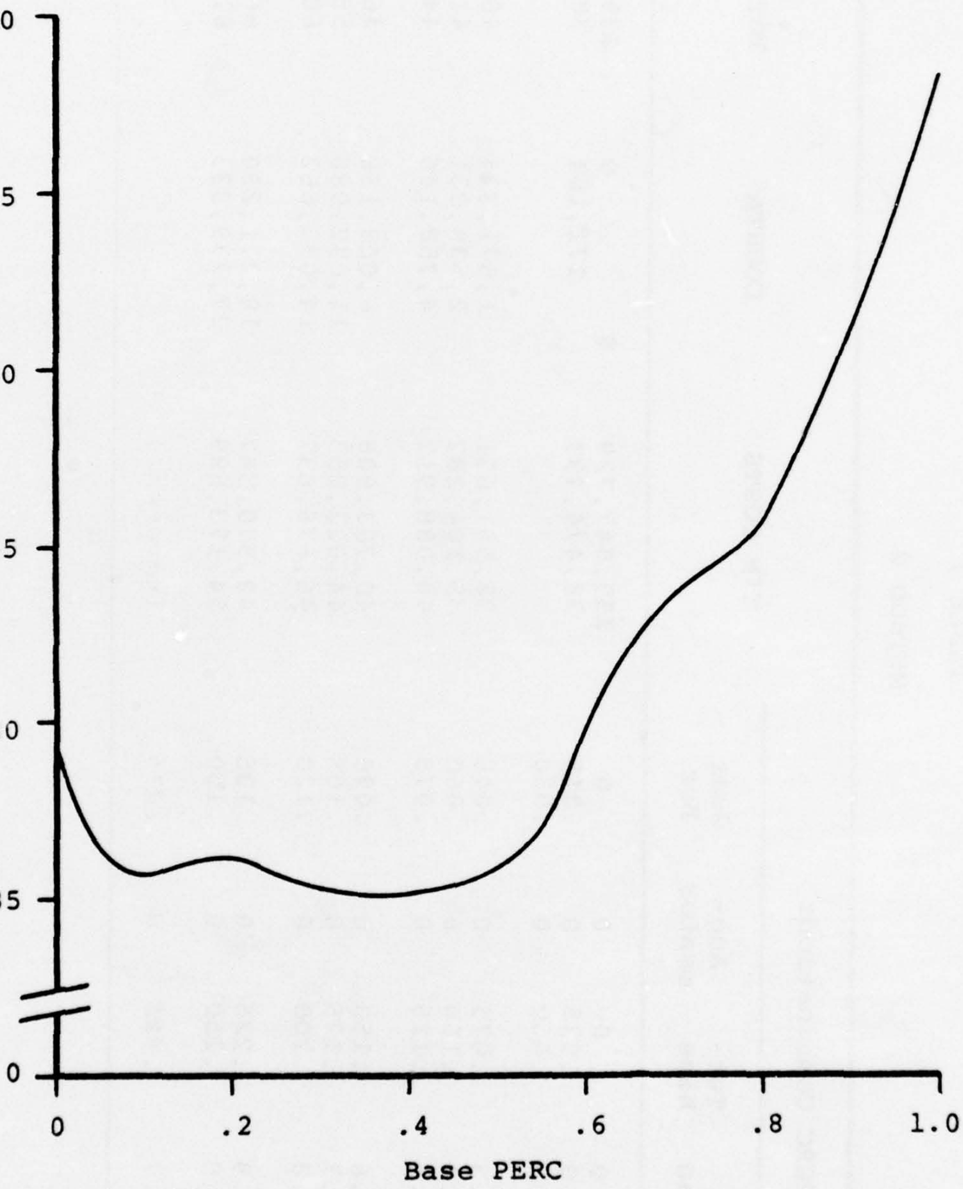

Fig. 8. PERC vs. TIN Method 1

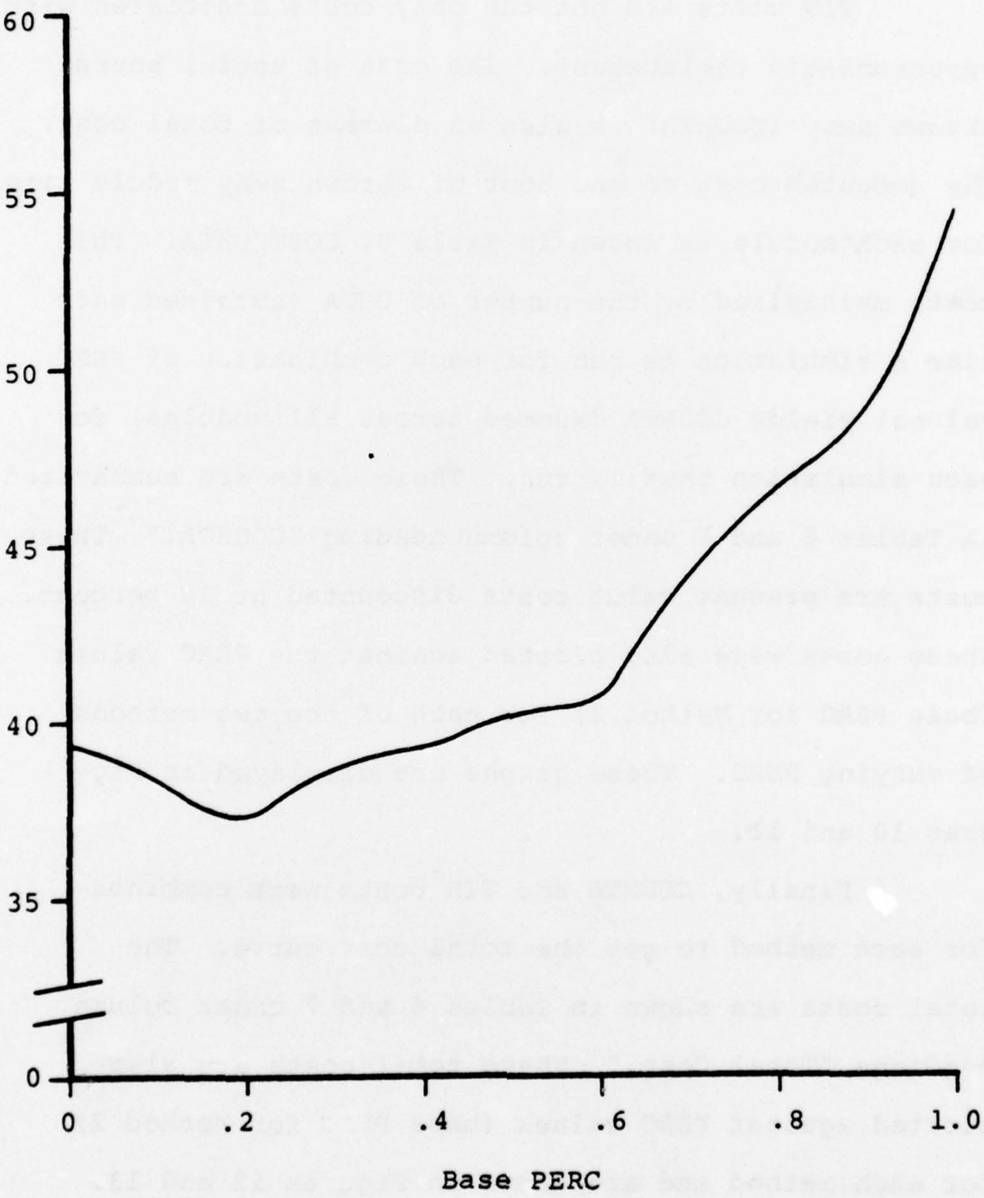

Fig. 9. Base PERC vs. TIN Method 2

were evaluated, there would be 161,051 such combinations.[27] The two graphs presented here represent only twenty-one combinations.

TIN costs are not the only costs associated with opportunistic replacement. The cost of useful hours thrown away (COUHTA) is also an element of total cost. The computed cost of one hour of thrown away module life for each module is shown in Table 8, COST/UHTA. This cost, multiplied by the number of UHTA (obtained each time a simulation is run for each combination of PERC values) yields COUHTA (summed across all modules) for each simulation that is run. These costs are summarized in Tables 6 and 7 under column heading "COUHTA." These costs are present value costs discounted at 10 percent. These costs were also plotted against the PERC values (base PERC for Method 2) for each of the two methods of varying PERC. These graphs are displayed in Figures 10 and 11.

Finally, COUHTA and TIN costs were combined for each method to get the total cost curve. The total costs are shown in Tables 6 and 7 under column headings "Total Cost." These total costs are also plotted against PERC values (base PERC for Method 2) for each method and are shown in Figures 12 and 13. Notice that since COUHTA increases at an increasing rate

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[27]See p. 53.

TABLE 8

COST/UHTA

	Core	Fan	Turbine	Aug-mentor*	Gear Box
Overhaul Costs (T)	101,483	27,402	32,858	N/A	4,225
MOT (hours)	2,160	3,600	1,920	N/A	1,000
COST/UHTA	$46.98	$7.61	$17.11	N/A	$4.23

*COST/UHTA is not required for the augmentor because it is not opportunistically replaced, and, consequently, no useful life is thrown away.

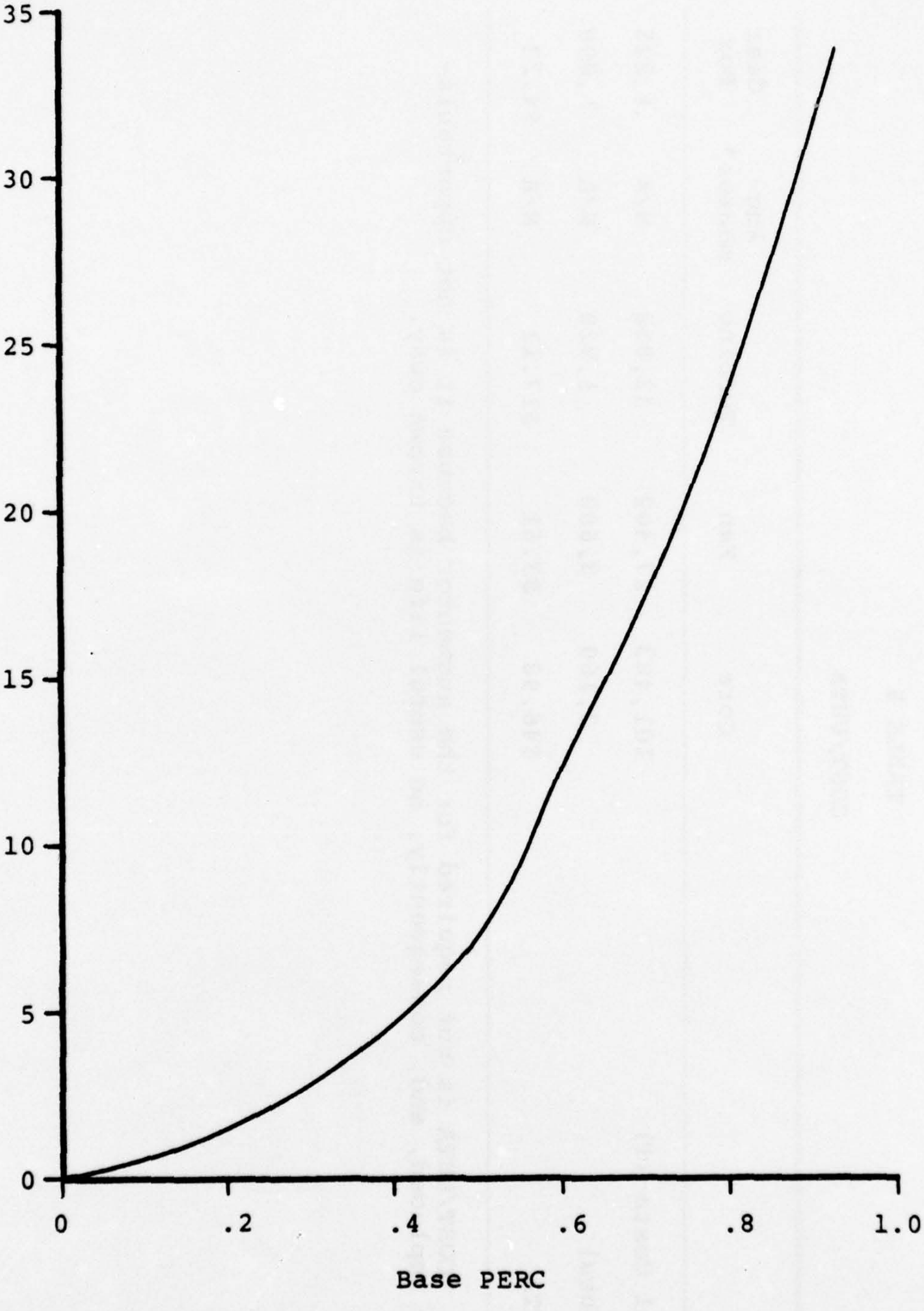

Fig. 10. PERC vs. COUHTA Method 1

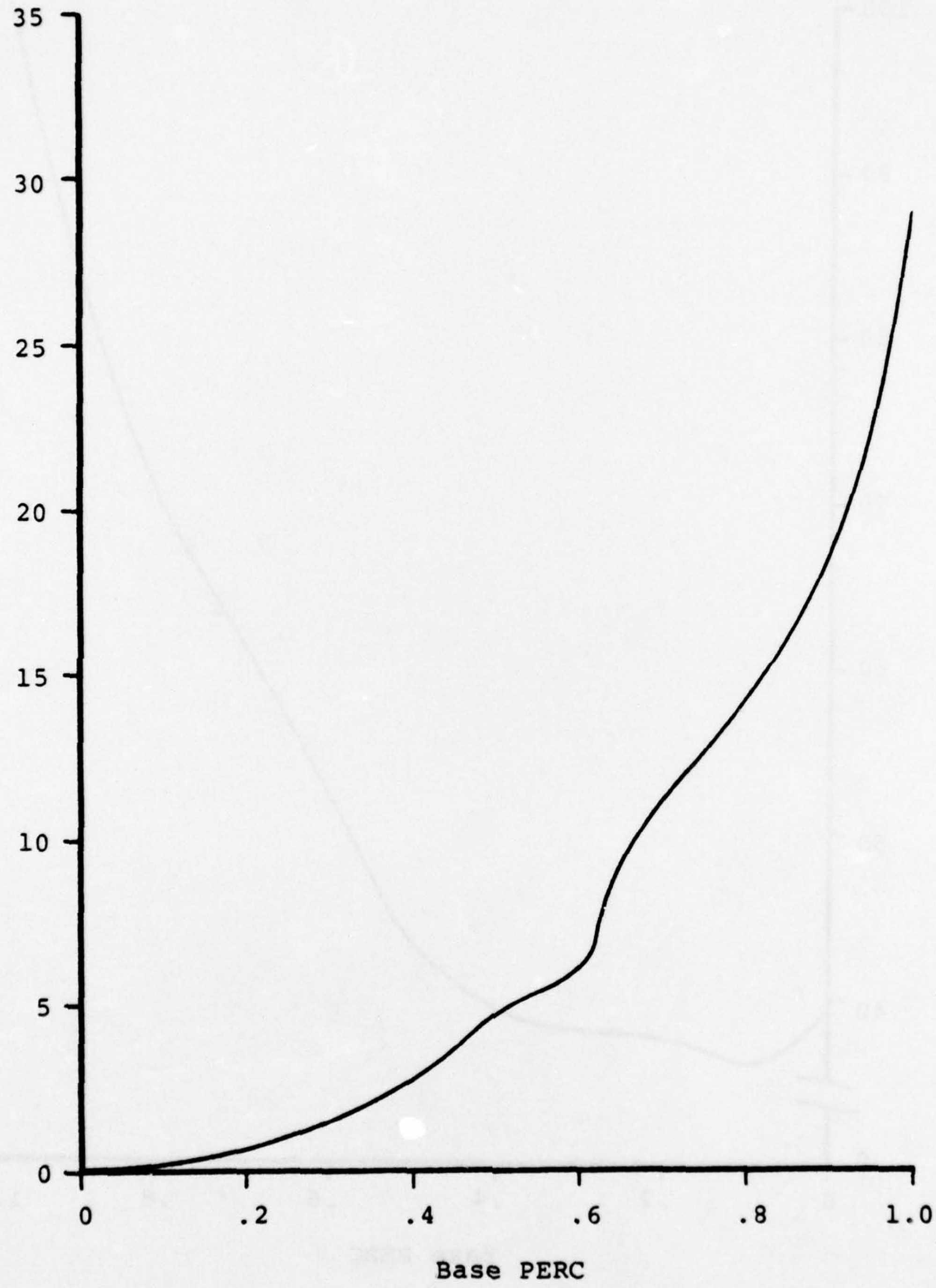

Fig. 11. Base PERC vs. COUHTA Method 2

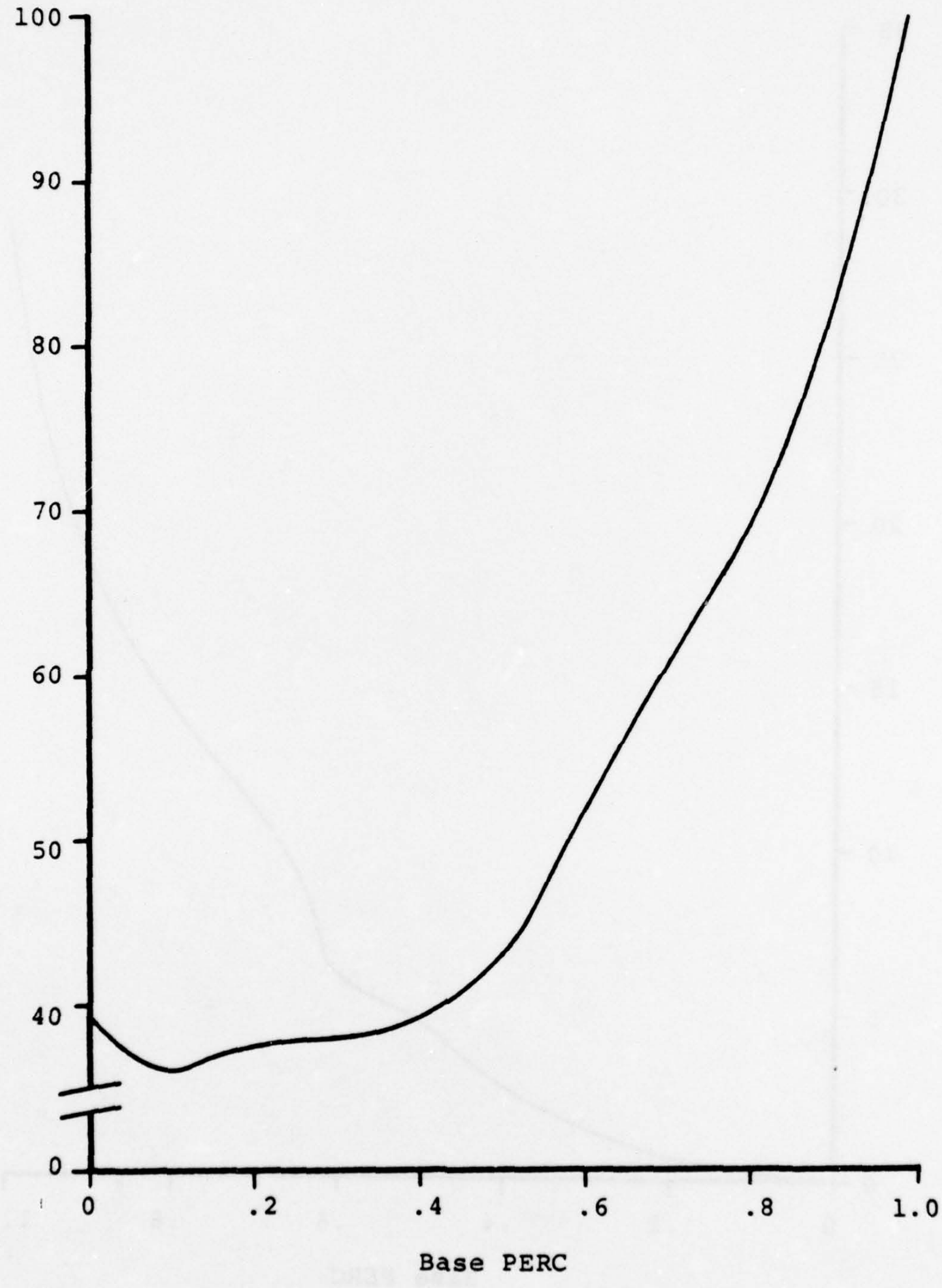

Fig. 12. PERC vs. Total Cost Method 1

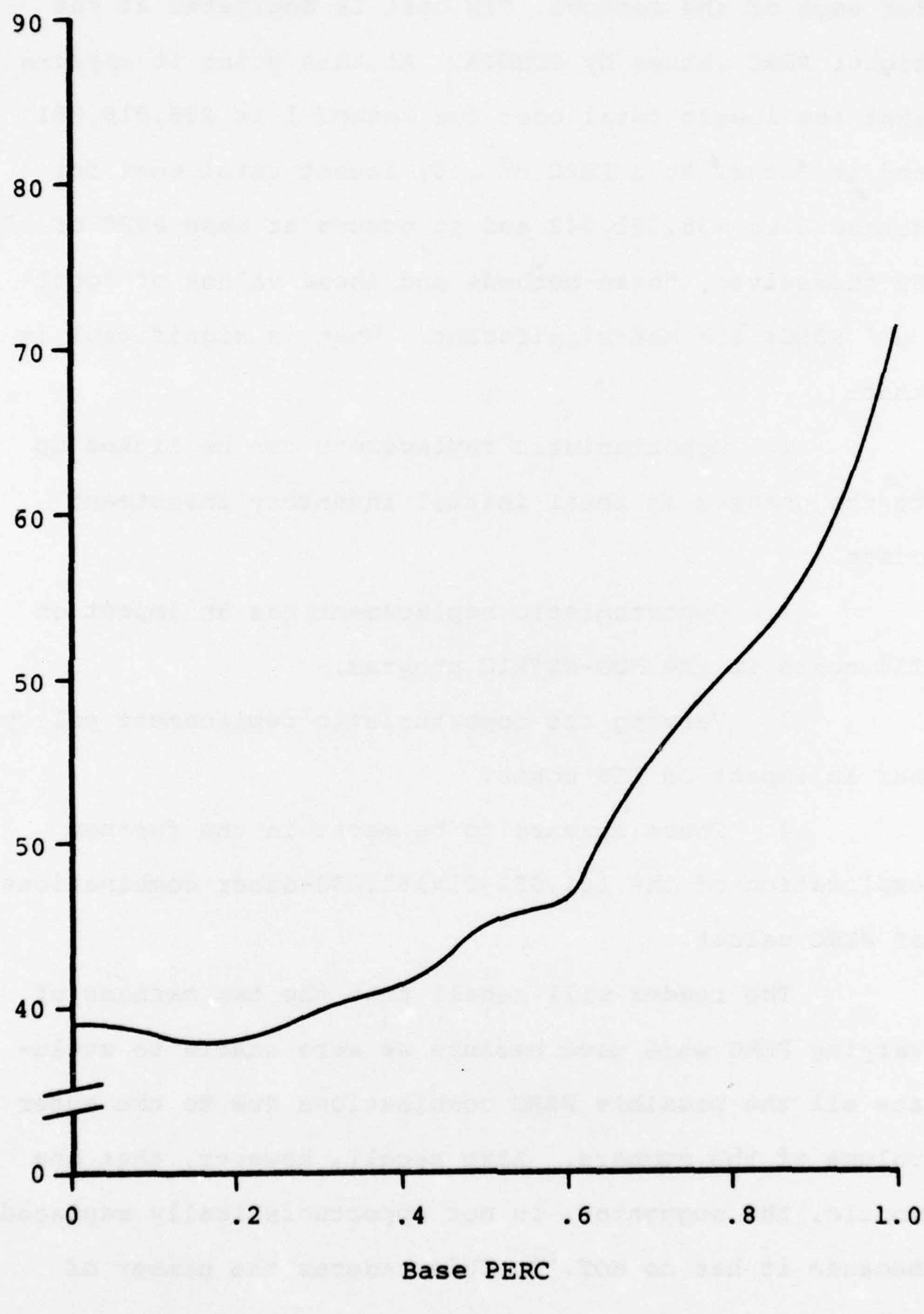

Fig. 13. Base PERC vs. Total Cost Method 2

for each of the methods, TIN cost is dominated at the higher PERC values by COUHTA. At this point it *appears* that the lowest total cost for Method 1 is $36,018,861 and it occurs at a PERC of .10; lowest total cost for Method 2 is $38,381,542 and it occurs at base PERC of .2. By themselves, these methods and these values of "optimum" PERCs are not significant. What is significant is that:

1. Opportunistic replacement *can* be linked up to the changes in total initial inventory investment costs.

2. Opportunistic replacement has an impact on TIN costs in the MOD-METRIC program.

3. Varying the opportunistic replacement policy has an impact on TIN costs.

4. There appears to be merit in the further exploration of the 161,051-21=161,030-other combinations of PERC values.

The reader will recall that the two methods of varying PERC were used because we were unable to evaluate all the possible PERC combinations due to the sheer volume of the numbers. Also recall, however, that one module, the augmentor, is not opportunistically replaced because it has no MOT.[28] This reduces the number of

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[28]See p. 70.

PERC combinations that need to be explored because the augmentor's PERC is constant and equals zero. In addition, if one were willing to explore only PERC values up to .6 (that is, an opportunistic policy calling for replacing a module opportunistically only if it has accrued operating hours that are *within* 60 percent of its MOT) *and* explore these values in increments of .2, then the number of combinations is simply $4^4=256$. This volume of analysis can be handled. It is important to note that the results of such an analysis cannot be graphed since there is no base PERC or a unique method of varying PERC. As each set of PERC combinations are input into the Simulation/MOD-METRIC algorithm a TIN cost is produced. This TIN cost is added to COUHTA obtained from the simulation to get a total cost. Each pair of total costs and PERC value sets represent a point in five-dimensional hyperspace (and there are 256 such points) because there is no way to order the PERC value sets along a single axis. The only analysis that can be performed on these points is to select the one with the lowest cost and say that this point is the best one *of the points studied*. The results of varying PERC in this manner are shown in Table 9, 256 PERC Combinations. The lowest total cost occurs when the PERC Combination shown in Table 10 is used.

TABLE 9

256 PERC COMBINATIONS

PERC Combinations					Total Costs
Core	Fan	Tur-bine	Aug-mentor	Gear Box	
0	.2	.2	0	.6	$32,922,621
0	0	.4	0	.6	33,604,154
0	0	.2	0	.4	33,821,978
0	.6	.2	0	.6	33,928,818
0	.4	.2	0	.4	33,960,785
0	.2	.4	0	.6	34,077,166
0	.2	.2	0	.4	34,122,037
0	.2	.4	0	.4	34,324,475
.2	.2	.4	0	.6	34,451,719
0	.2	.2	0	.2	34,463,856
0	.4	.4	0	.6	34,596,366
0	0	0	0	.6	34,734,598
0	0	.2	0	.2	34,750,007
0	.4	.4	0	.4	34,798,674
0	.2	0	0	.6	34,813,093
0	.4	0	0	.4	34,838,096
.2	0	.4	0	.6	34,933,601
.2	.4	.2	0	.6	34,946,683
0	.2	0	0	.4	35,010,529
.2	.2	.2	0	.4	35,055,191
.2	.4	0	0	.6	35,191,304
0	.6	.2	0	.4	35,230,894
0	0	.4	0	.4	35,277,885
0	.2	.4	0	.2	35,434,669
0	.6	.4	0	.6	35,612,645
.2	.2	.2	0	.6	35,618,044
0	.4	0	0	.6	35,641,886
0	.4	.2	0	.2	35,703,733
0	.6	.2	0	.2	35,790,902
.2	.6	.2	0	.6	35,887,765

TABLE 9--Continued

PERC Combinations					Total Costs
Core	Fan	Tur-bine	Aug-mentor	Gear Box	
.2	.2	0	0	.6	$36,000,477
0	.2	0	0	.2	36,005,021
0	0	.4	0	.2	36,070,221
0	.6	.4	0	.4	36,266,453
0	.4	.2	0	.6	36,309,946
0	.6	0	0	.6	36,418,242
0	.4	.6	0	.6	36,492,485
.2	0	.4	0	.4	36,501,236
.2	.2	0	0	.4	36,501,381
.2	0	.2	0	.4	36,543,460
0	.6	0	0	.4	36,566,087
.2	0	0	0	.4	36,573,052
0	0	0	0	.4	36,628,128
.2	.4	0	0	.2	36,706,838
0	.4	.4	0	.2	36,728,504
.2	.2	.4	0	.4	36,737,600
.2	.2	0	0	.6	36,829,670
.2	0	0	0	.6	36,950,894
.2	0	.2	0	.2	37,123,512
0	.2	.6	0	.6	37,162,589
0	.4	0	0	.2	37,171,425
0	.6	.4	0	.2	37,218,602
.4	0	0	0	.6	37,222,514
0	0	0	0	.4	37,227,332
0	.2	.2	0	0	37,264,504
.2	.4	.2	0	.4	37,265,463
.2	.6	.2	0	.4	37,381,455
.2	.4	0	0	.2	37,405,949
.2	0	.4	0	.2	37,454,361
0	0	.6	0	.4	37,600,411

TABLE 9--Continued

PERC Combinations					Total Costs
Core	Fan	Tur-bine	Aug-mentor	Gear Box	
.2	.4	.2	0	.2	$37,716,968
0	.2	.4	0	0	37,780,599
.2	.6	.4	0	.6	37,806,168
.2	.4	.4	0	.4	37,814,011
0	.2	.6	0	.4	37,887,263
0	.4	.2	0	0	37,887,830
0	0	.2	0	0	37,897,934
.2	.6	0	0	.4	37,917,132
.2	.2	0	0	.2	37,992,405
0	0	.6	0	.6	38,020,469
.2	.6	0	0	.6	38,183,998
0	.6	.6	0	.6	38,248,999
0	.4	.6	0	.4	38,253,796
.2	.6	.2	0	.2	38,287,467
.2	0	0	0	.2	38,406,519
.2	0	.6	0	.4	38,430,148
.2	.2	.2	0	0	38,506,268
.2	.6	.4	0	.4	38,514,557
.2	.2	.4	0	.2	38,590,830
0	.2	0	0	0	38,677,279
0	.6	.4	0	0	38,752,655
0	.6	0	0	.8	38,790,399
.4	0	.2	0	.6	38,874,871
.2	0	.6	0	.6	38,898,755
.4	.2	.2	0	.4	38,944,615
.4	.2	.4	0	.6	39,014,164
.2	.4	.4	0	.2	39,029,352
0	.4	.4	0	0	39,033,665
0	0	0	0	0	39,047,729
.4	.2	.2	0	.6	39,081,301

TABLE 9--Continued

PERC Combinations					Total Costs
Core	Fan	Tur-bine	Aug-mentor	Gear Box	
0	0	.4	0	0	$39,107,560
.2	.2	.6	0	.6	39,109,918
.4	.4	0	0	.6	39,144,627
.2	.6	.4	0	.2	39,154,339
.4	0	.2	0	.4	39,225,718
.2	.2	.4	0	0	39,253,815
0	0	.6	0	.2	39,256,314
.4	.4	.4	0	.6	39,341,961
0	.4	0	0	0	39,401,373
.2	.2	.6	0	.4	39,468,930
0	.6	.2	0	0	39,493,692
.2	.6	0	0	.2	39,504,212
.4	.4	.2	0	.6	39,520,096
0	.6	.6	0	.4	39,557,196
.2	0	.2	0	0	39,573,013
.4	.2	.4	0	.4	39,648,445
.2	.4	.4	0	0	39,706,966
.2	.4	.2	0	0	39,776,954
.4	0	.4	0	.6	39,802,104
.4	.4	.4	0	.4	39,847,598
.2	.4	.6	0	.6	39,867,962
.4	.6	.4	0	.6	39,882,978
0	.2	.6	0	.2	39,884,210
.4	.4	.2	0	.4	39,946,200
.2	0	.4	0	0	39,979,705
.4	0	.4	0	.4	40,083,738
0	.6	0	0	0	40,125,343
.4	.2	0	0	.4	40,338,351
.4	.4	0	0	.6	40,343,610
.4	.6	.2	0	.6	40,598,622
0	.4	.6	0	.2	40,661,967
.2	.6	.6	0	.6	40,765,795
.4	.4	0	0	.4	40,787,031

TABLE 9--Continued

PERC Combinations					Total Costs
Core	Fan	Tur-bine	Aug-mentor	Gear Box	
0	0	.6	0	0	$40,820,732
.2	.6	.2	0	0	40,848,120
.2	0	0	0	0	40,883,758
.2	.4	0	0	0	40,894,940
.2	.2	0	0	0	40,971,935
.4	0	.2	0	.2	40,982,597
.4	.2	.2	0	.2	41,090,735
.4	.2	.4	0	.2	41,129,177
.2	.6	.6	0	.4	41,164,609
.2	.2	.6	0	.2	41,165,221
.4	.6	.2	0	.4	41,244,823
.2	.6	.4	0	0	41,328,672
.2	.4	.6	0	.4	41,361,537
.4	0	0	0	.2	41,511,752
.4	.6	0	0	.6	41,572,077
0	.6	0	0	.2	41,683,624
0	.6	.6	0	0	41,704,041
0	.2	.6	0	0	41,747,648
.4	.6	.4	0	.4	41,791,609
.4	0	0	0	.4	41,912,580
.4	.2	.6	0	.4	41,930,900
.4	.6	.4	0	.2	41,954,634
.2	.4	.6	0	.2	42,034,755
.4	.4	.2	0	.2	42,038,033
.4	.6	0	0	.4	42,066,431
.4	0	.4	0	.2	42,178,714
.4	.2	.6	0	.6	42,211,990
.2	0	.6	0	0	42,213,957
.2	.6	0	0	0	42,228,244
.4	.4	.4	0	.2	42,301,265
0	.4	.6	0	0	42,326,784
.2	.6	.6	0	.2	42,385,090
.4	.6	.2	0	.2	42,728,492

TABLE 9--Continued

PERC Combinations					Total Costs
Core	Fan	Tur-bine	Aug-mentor	Gear Box	
.4	.4	0	0	.2	$42,778,007
.4	.4	.6	0	.6	42,870,936
.2	.2	.6	0	0	42,880,594
.4	.2	0	0	.2	42,912,463
.4	0	.6	0	.4	42,991,154
.4	0	.6	0	.6	43,056,118
.2	.4	.6	0	0	43,103,543
.4	.2	.4	0	0	43,462,364
.4	.4	.6	0	.4	43,530,085
.4	.4	.2	0	0	43,591,916
.4	.4	.4	0	0	43,827,507
.4	.2	.2	0	0	44,020,376
.4	.4	0	0	0	44,079,627
.4	0	.2	0	0	44,091,765
.4	0	.4	0	0	44,157,524
.2	.6	.6	0	0	44,204,272
.4	.6	0	0	.2	44,247,498
.4	.6	.6	0	.6	44,273,382
.4	.2	0	0	0	44,428,267
.4	.6	0	0	0	44,552,724
.4	0	0	0	0	44,576,187
.4	.6	.4	0	0	44,977,010
.4	.6	.6	0	.4	45,015,132
.4	.2	.6	0	.2	45,099,894
.4	0	.6	0	.2	45,472,232
.4	.6	.2	0	0	45,597,045
.4	.4	.6	0	.2	45,699,811
.4	.2	.6	0	0	46,167,210
.4	0	.6	0	0	46,596,218
.4	.6	.6	0	.2	46,843,737
.6	0	.2	0	.6	47,218,071
.6	.2	.4	0	.6	47,467,347
.4	.4	.6	0	0	47,474,784

TABLE 9--Continued

PERC Combinations					Total Costs
Core	Fan	Tur-bine	Aug-mentor	Gear Box	
.6	0	.4	0	.6	$47,662,126
.6	0	.2	0	.4	48,530,186
.4	.6	.6	0	0	48,633,852
.6	.2	.2	0	.4	48,786,291
.6	.2	.2	0	.6	48,929,537
.6	.4	.2	0	.4	48,950,658
.6	.4	.4	0	.6	48,966,778
.6	.2	.4	0	.4	49,052,794
.6	.4	.4	0	.4	49,254,118
.6	.4	.2	0	.6	49,517,405
.6	.2	0	0	.6	49,881,186
.6	0	0	0	.6	49,966,345
.6	.6	.2	0	.6	50,020,079
.6	0	.2	0	.2	50,033,541
.6	.6	.2	0	.4	50,227,486
.6	0	.4	0	.4	50,246,546
.6	.4	0	0	.6	50,433,497
.6	0	0	0	.4	50,510,565
.6	.6	.4	0	.6	50,670,646
.6	.6	0	0	.6	50,778,408
.6	0	.4	0	.4	51,078,230
.6	.2	0	0	.4	51,099,006
.6	.4	0	0	.4	51,109,864
.6	.2	.4	0	.2	51,161,872
.6	.2	.2	0	.2	51,249,219
.6	.6	0	0	.4	51,418,998
.6	.2	.6	0	.6	51,551,400
.6	.4	.2	0	.2	51,783,715
.6	.4	.6	0	.4	52,215,072
.6	.6	.2	0	.2	52,337,419

TABLE 9--Continued

PERC Combinations					Total Costs
Core	Fan	Tur-bine	Aug-mentor	Gear Box	
.6	0	.4	0	.2	$52,471,000
.6	0	.6	0	.6	52,627,505
.6	.4	.6	0	.6	52,634,940
.6	.6	.4	0	.2	52,767,724
.6	.2	.6	0	.4	52,820,124
.6	.6	0	0	.2	53,020,306
.6	.2	0	0	.2	53,028,171
.6	.2	.4	0	0	53,111,332
.6	.4	0	0	.2	53,390,856
.6	0	.6	0	.4	53,410,796
.6	.4	.4	0	.2	53,417,007
.6	.2	.2	0	0	53,763,259
.6	.4	.4	0	0	53,766,841
.6	0	.2	0	0	53,860,798
.6	.6	.6	0	.4	53,906,794
.6	.6	.6	0	.6	53,941,181
.6	0	0	0	.2	53,992,626
.6	.2	0	0	0	54,000,485
.6	.4	.2	0	0	54,537,108
.6	.4	0	0	0	54,639,903
.6	.6	.2	0	0	54,814,307
.6	0	0	0	0	54,932,945
.6	.6	.4	0	0	55,022,135
.6	.4	.6	0	.2	55,161,073
.6	.6	0	0	0	55,186,569
.6	.2	.6	0	.2	55,351,291
.6	0	.4	0	0	55,413,126
.6	0	.6	0	.2	55,986,227
.6	.2	.6	0	0	56,607,120
.6	.6	.6	0	.2	56,711,818

TABLE 9--Continued

PERC Combinations					Total Costs
Core	Fan	Tur-bine	Aug-mentor	Gear Box	
.6	0	.6	0	0	$57,594,804
.6	.4	.6	0	0	58,808,315
.6	.6	.6	0	0	58,910,921

TABLE 10

OPTIMUM PERC COMBINATION NO. 1

	Core	Fan	Turbine	Augmentor	Gearbox
PERC	0	.2	.2	0	.6

The total cost for this combination is $32,922,621. Note that the lowest cost occurs when one of the modules has a PERC of .6. This result led us to explore the PERC values around this combination in greater detail. The PERC values shown in Table 11, Twenty Six More PERC Combinations, were explored. The resulting total costs for each combination are also shown in Table 11. The lowest total cost occurs when the PERC combination shown in Table 12 is used. The total cost for this combination was $32,731,150. Again, the lowest cost occurs when one of the modules has a PERC of .65. This result led us to search for an even lower total cost around this PERC combination area. We left the PERCs for the core, fan, turbine, and augmentor as shown in Table 12 and increased the gearbox PERC from .7 to .9 in .1 increments. The results of this search are shown in Table 13, Three More Combinations. The lowest total cost in this table occurs when the gearbox module PERC is .8. The total cost for this combination is $33,157,588.

Of all the PERC combinations that were explored, including the PERCs explored in Methods 1 and 2 for varying PERC, the lowest cost, $32,731,150, was achieved using the PERC combination shown in Table 12. The reader should be aware that this combination is not an optimal solution but rather the best solution of all the combinations studied.

TABLE 11

TWENTY-SIX MORE PERC COMBINATIONS

PERC Combinations					Total Costs
Core	Fan	Turbine	Augmentor	Gear Box	
0	.15	.15	0	.65	$32,731,150
0	.25	.20	0	.65	32,853,315
0	.20	.20	0	.65	32,966,517
0	.25	.20	0	.60	33,013,896
0	.15	.25	0	.65	33,059,317
0	.15	.20	0	.55	33,089,282
0	.25	.25	0	.65	33,092,480
0	.20	.25	0	.50	33,146,407
0	.15	.20	0	.65	33,159,242
0	.25	.15	0	.65	33,368,785
0	.20	.15	0	.50	33,415,833
0	.15	.15	0	.55	33,433,728
0	.20	.25	0	.65	33,501,925
0	.20	.15	0	.60	33,685,721
0	.20	.20	0	.55	33,701.887
0	.25	.25	0	.55	33,771,245
0	.25	.20	0	.55	33,915,132
0	.15	.25	0	.60	33,923,972
0	.25	.15	0	.55	34,001,045
0	.20	.25	0	.60	34,083,354
0	.15	.25	0	.55	34,091,064
0	.15	.15	0	.60	34,146,890
0	.15	.20	0	.60	34,264,522
0	.25	.25	0	.60	34,382,089
0	.20	.15	0	.65	34,486,372

TABLE 12

OPTIMUM PERC COMBINATION NO. 2

	Core	Fan	Turbine	Augmentor	Gearbox
PERC	0	.15	.15	0	.65

TABLE 13

THREE MORE COMBINATIONS

PERC Combinations					Total Costs
Core	Fan	Tur- bine	Aug- mentor	Gear Box	
0	.15	.15	0	.80	$33,157,558
0	.15	.15	0	.90	33,191,414
0	.15	.15	0	.70	33,656,120

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

It will be recalled that the first research question was: *What impact does opportunistic replacement have on spare engine and module inventory investment?* Based on simulation results, MOD-METRIC results, and the limiting assumptions on page 59, we concluded that opportunistic replacement does have an effect on inventory investment. As opportunistic replacement of a module increases, engine mean time between demands increases and module mean time between demands decreases (page 78). This characteristic, in turn, changes the amount of inventory investment required to support the MOD-METRIC performance level of one expected backorder (page 90).

The second research question was: *What effect does varying the opportunistic replacement policy (PERC) have on spare engine and module inventory investment?* We found (for our two-base, ten-year model) that by increasing PERC from 0 percent on all modules simultaneously in increments of 10 percent, the required inventory investment dropped from approximately $39 million for 0 percent PERC to an approximate minimum

of $35 million for 40 percent PERC. This curve then rose steadily as PERC increased to 100 percent. The curve appeared relatively flat in the region between 10 percent and 50 percent PERC. Recall that Method 2 incremented PERC according to size of the MTBFs for each module. For this method, the required investment dropped from $39 million to $36 million at 10 percent PERC and then began to rise again as PERC moved toward 100 percent. This curve also appears relatively flat in the region from 10 percent to 30 percent.

The third question was: *Can the opportunistic replacement policy (PERC) be varied to achieve a minimum of total costs due to combined (TIN costs) and cost of useful hours thrown away (COUHTA)?* We answered this question with calculations which yielded a minimum combined TIN cost and COUHTA *for the range of PERCs that we studied.* When PERC was incremented uniformly across all modules the inclusion of COUHTA shifted the optimum PERC from 40 percent to 10 percent and resulted in a total cost of $36.0 million. When PERC was incremented by a weighted amount based on module MTBF the optimum PERC did not shift and total costs were $38.7 million.

Finally, we explored 256 different combinations of PERC in an effort to improve on the total cost minimums from the first two methods. The results of these

PERC combinations ranged from a high of \$58.9 million to a low of \$32.7 million. Inspection of the PERC combination resulting in the lowest total cost fosters the idea that low total costs can be achieved by decreasing PERC values for modules that are expensive to overhaul, and by increasing PERC values for modules that are inexpensive to overhaul. This idea is not a mathematical assertion but simply an observation of an apparent trend in the results *of the policies studied.*

Recommendations

We feel that the Simulation/MOD-METRIC approach to the study of opportunistic replacement of jet engine modules bears further investigation. The model as it stands now (two bases, ten years, ten assumptions), predicts \$6.3 million savings over nonopportunistic replacement if the best PERC combination we found is used. Since the total system cost of spare engines and modules without opportunistic replacement was \$39 million, a 16 percent cost reduction is predicted for our system if the best PERC is employed. We judge this percentage to be worthy of further interest. Incorporation of the following suggestions would improve the model's realism.

1. The effect of opportunistic replacement on average depot and base repair times should be studied. We feel that opportunistic replacement may cause the

repair workload distribution to shift by some amount from base level to depot level.

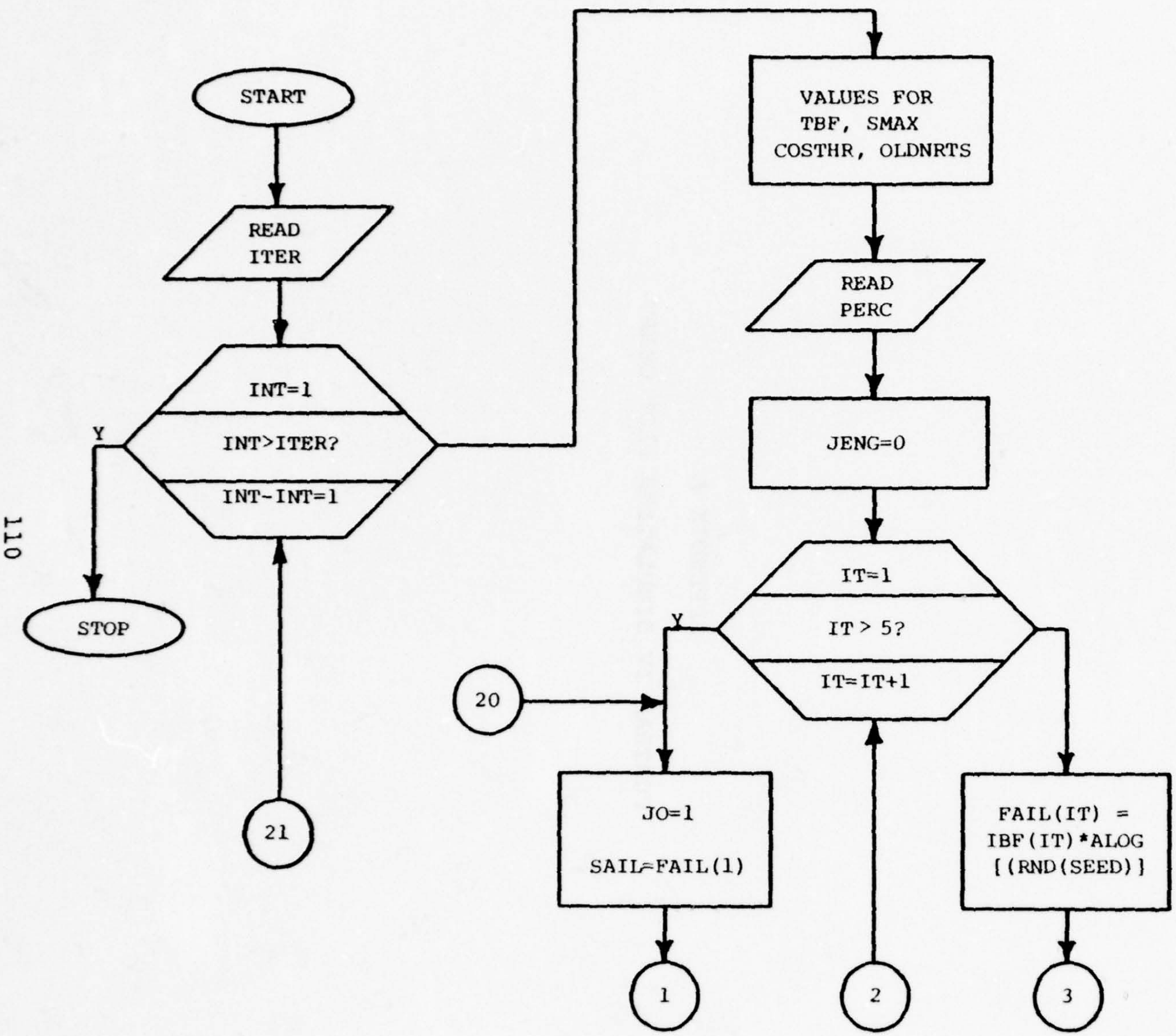
2. The simulation should be connected to MOD-METRIC within the computer so that more combinations of PERC can be considered. We were limited in how many we could consider because we had to manually input simulation results for each different set of PERCs into the MOD-METRIC program.

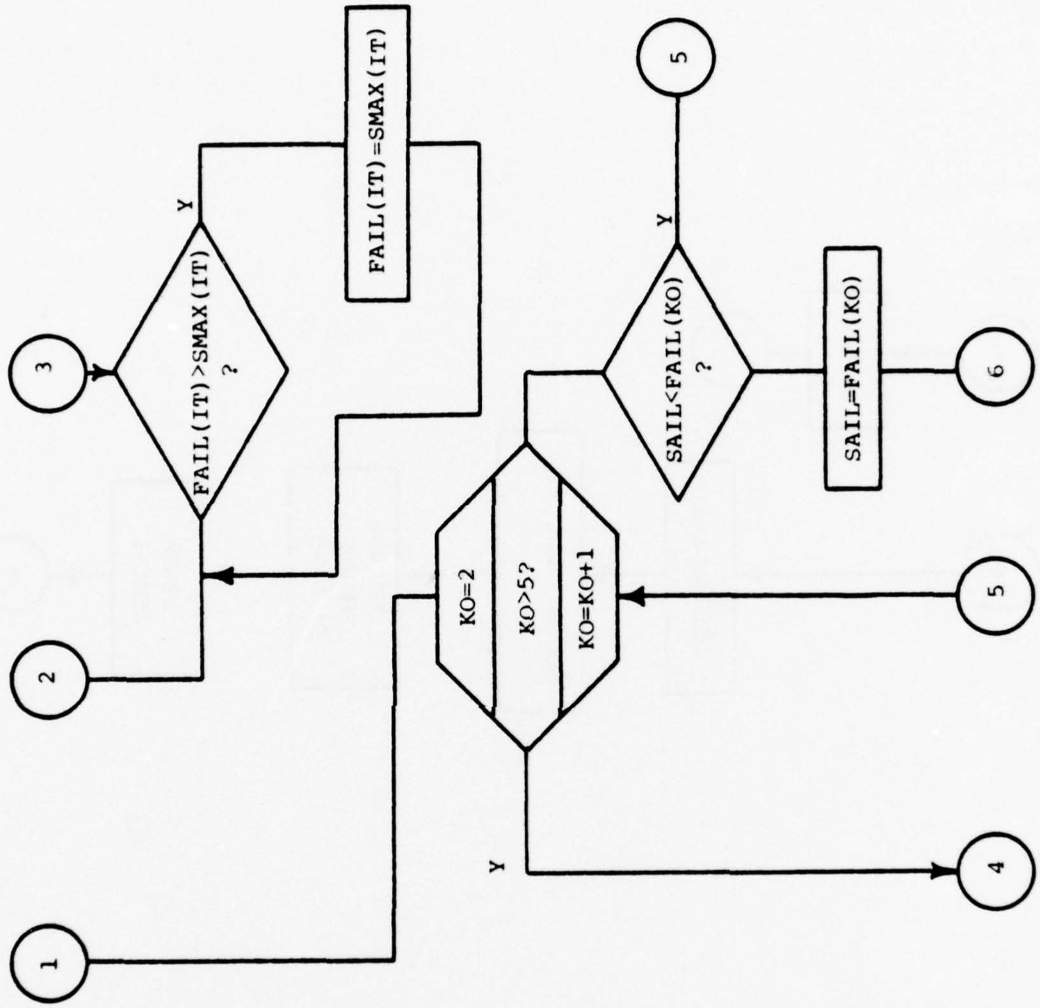
3. The structure of the MOD-METRIC program should be studied to determine the feasibility of improving the accuracy of investment requirements when opportunistic replacement is employed. Improvement of accuracy entails modification of MOD-METRIC to include probabilities of replacing two or more modules at the same time (see Assumption 10, page 61).

APPENDIXES

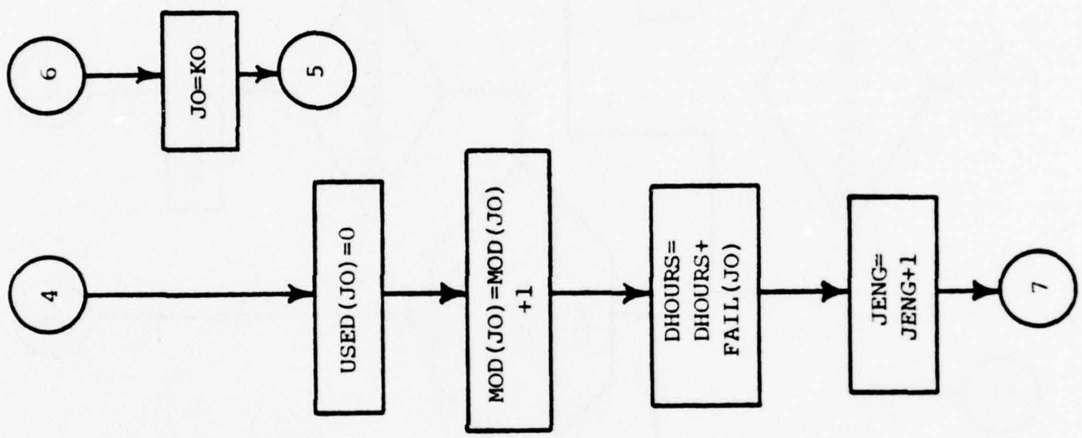
APPENDIX A

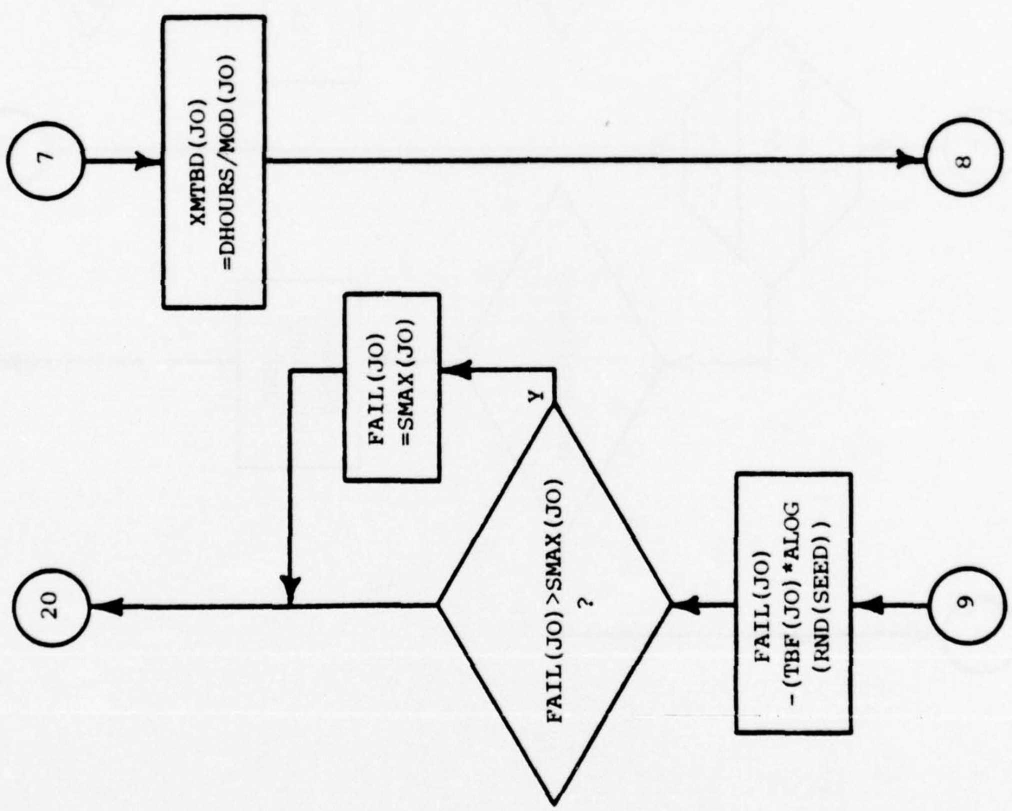
FORTRAN IV SIMULATION FLOW CHART

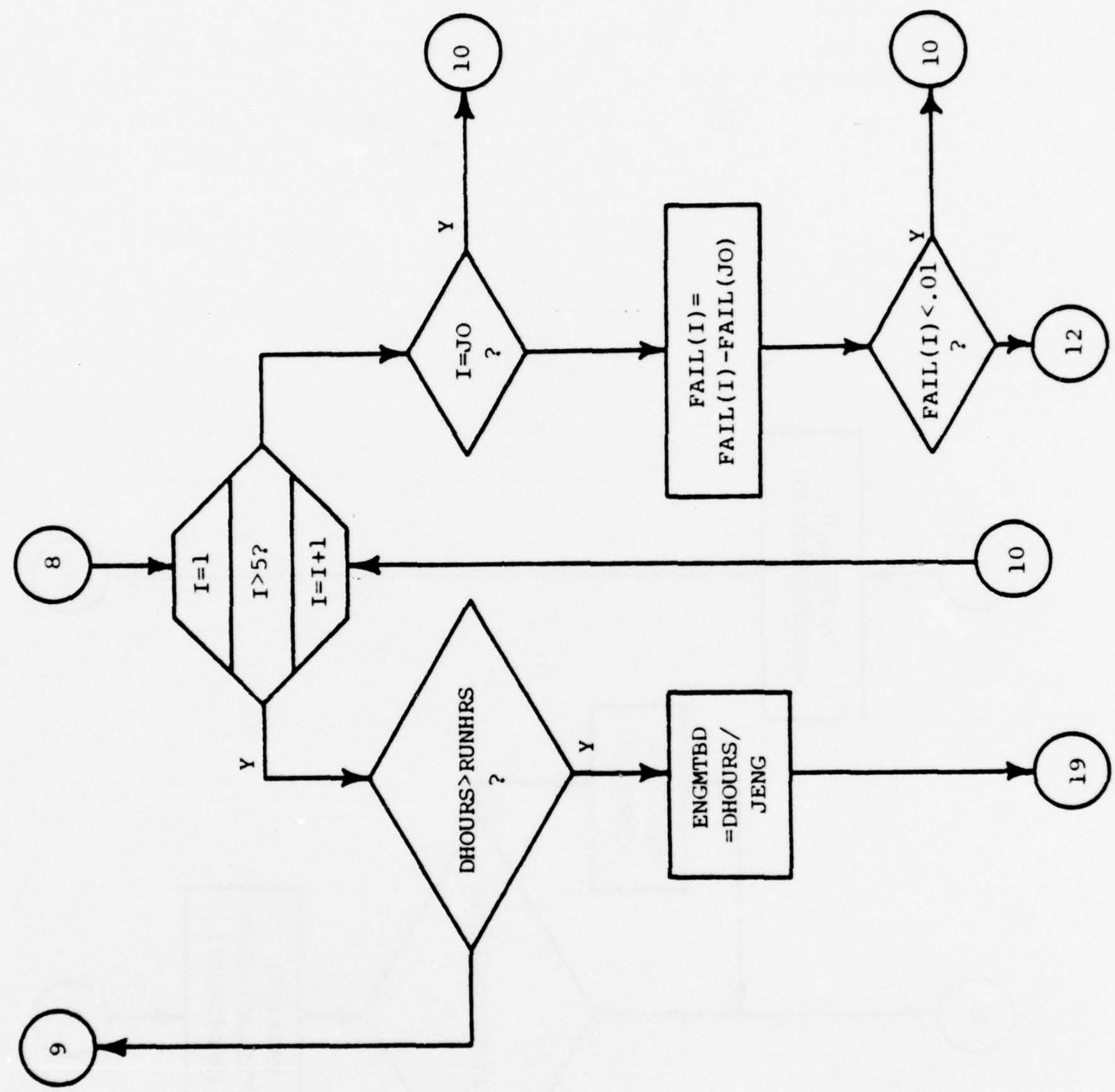

START
READ
ITER
INT=1
INT>ITER?
INT-INT=1
Y
STOP
21
VALUES FOR
TBF, SMAX
COSTHR, OLDNRTS
READ
PERC
JENG=0
IT=1
IT > 5?
IT=IT+1
Y
20
JO=1
SAIL=FAIL(1)
FAIL(IT) =
IBF(IT)*ALOG
[(RND(SEED)]
1
2
3

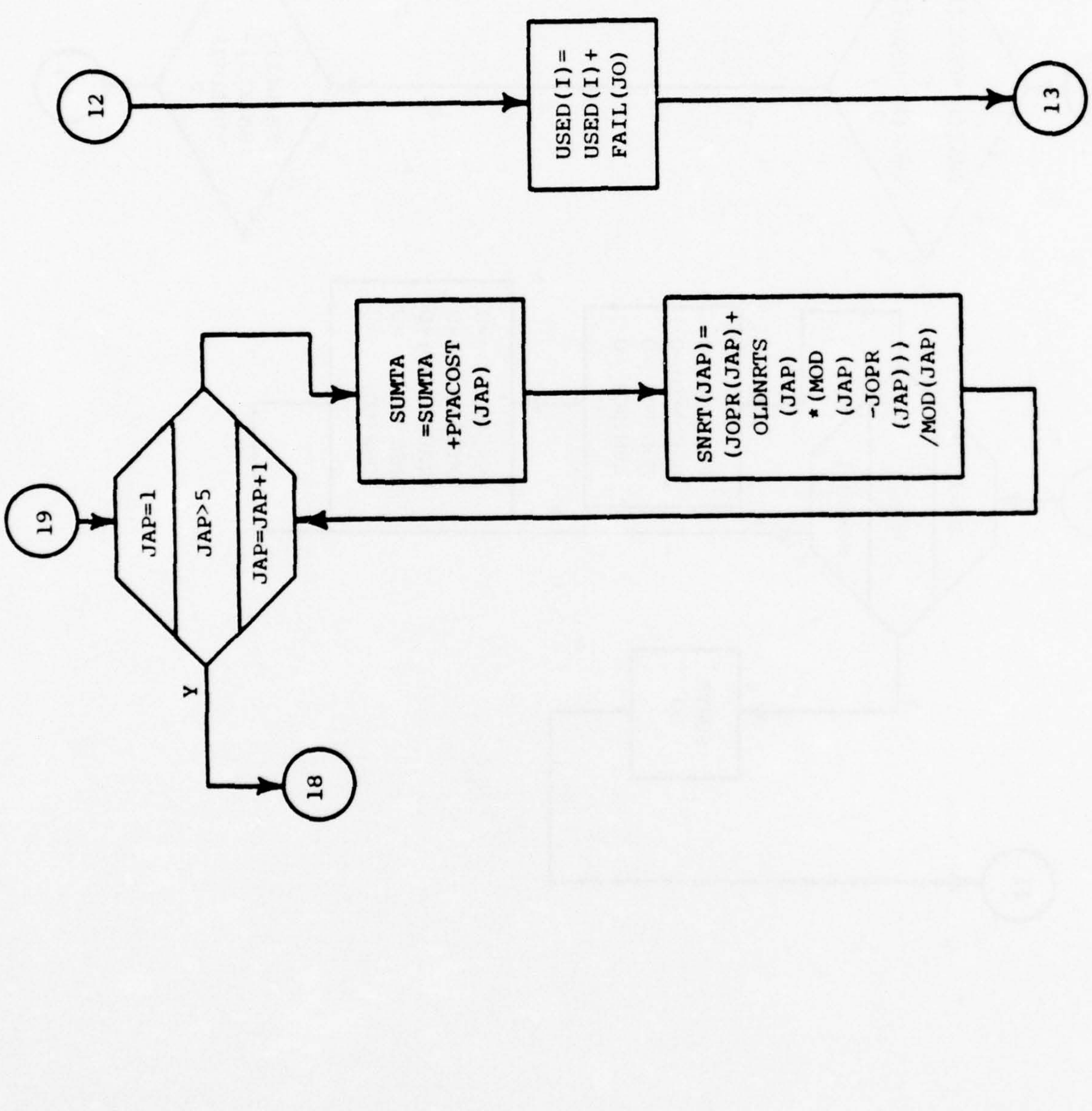


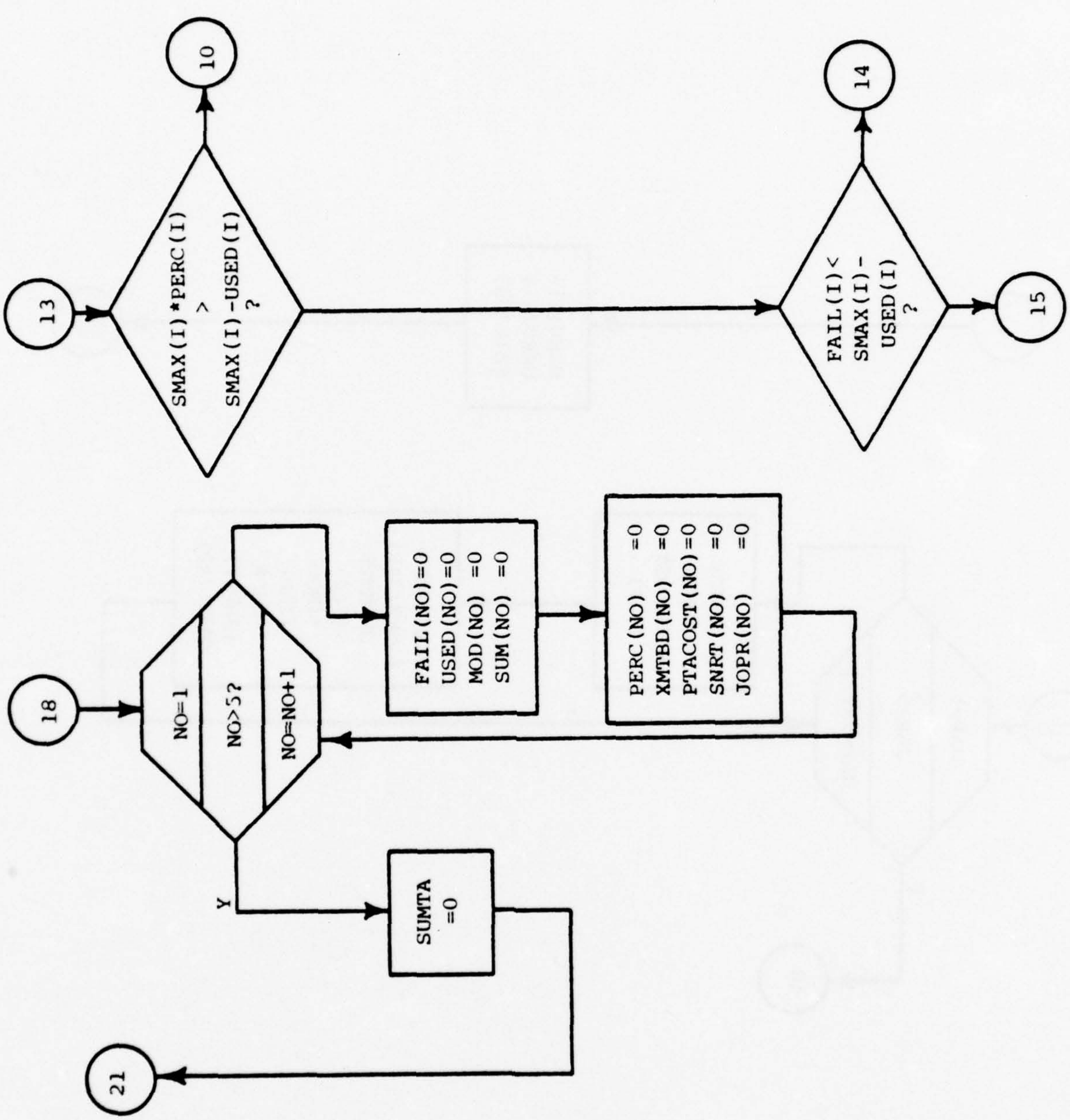
FAIL(IT)>SMAX(IT)
?
Y
FAIL(IT)=SMAX(IT)
KO=2
KO>5?
KO=KO+1
Y
SAIL<FAIL(KO)
?
Y
SAIL=FAIL(KO)
1
2
3
4
5
5
6

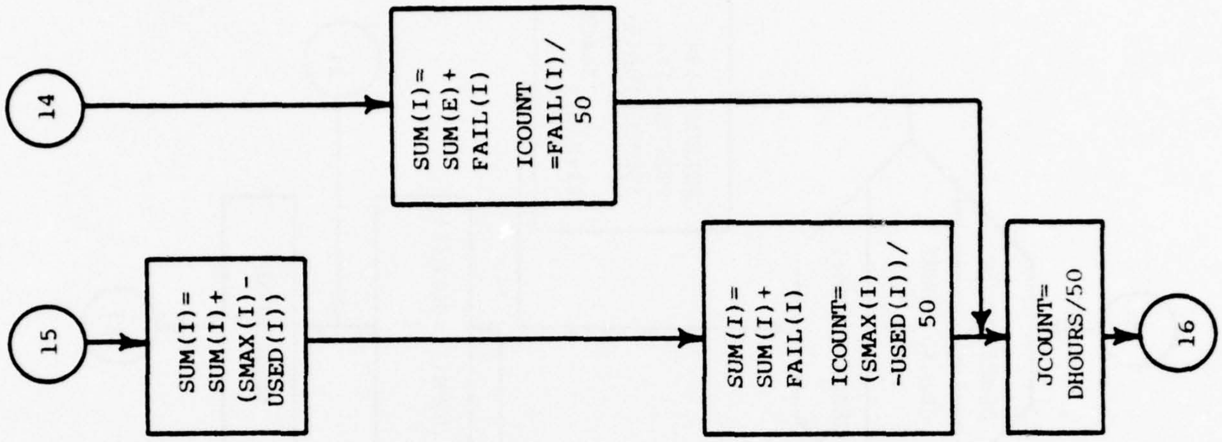

6
JO=KO
5
4
USED(JO)=0
MOD(JO)=MOD(JO)
+1
DHOURS=
DHOURS+
FAIL(JO)
JENG=
JENG+1
7

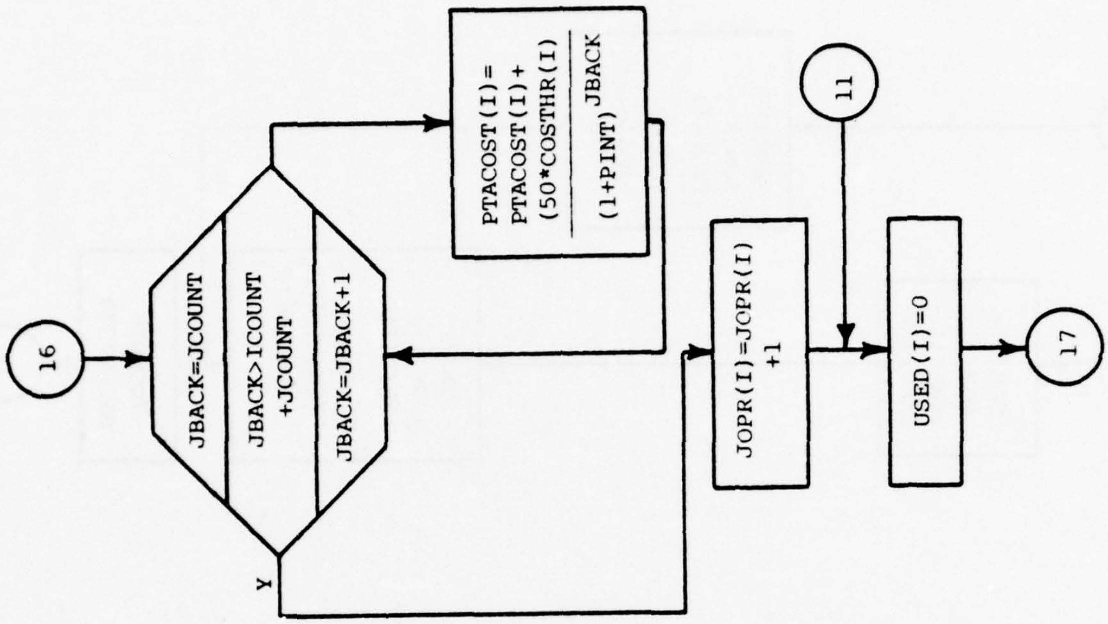

7
XMTBD (JO)
=DHOURS/MOD (JO)
8
FAIL (JO)
=SMAX (JO)
Y
20
FAIL (JO) >SMAX (JO)
?
FAIL (JO)
- (TBF (JO) *ALOG
(RND (SEED))
9

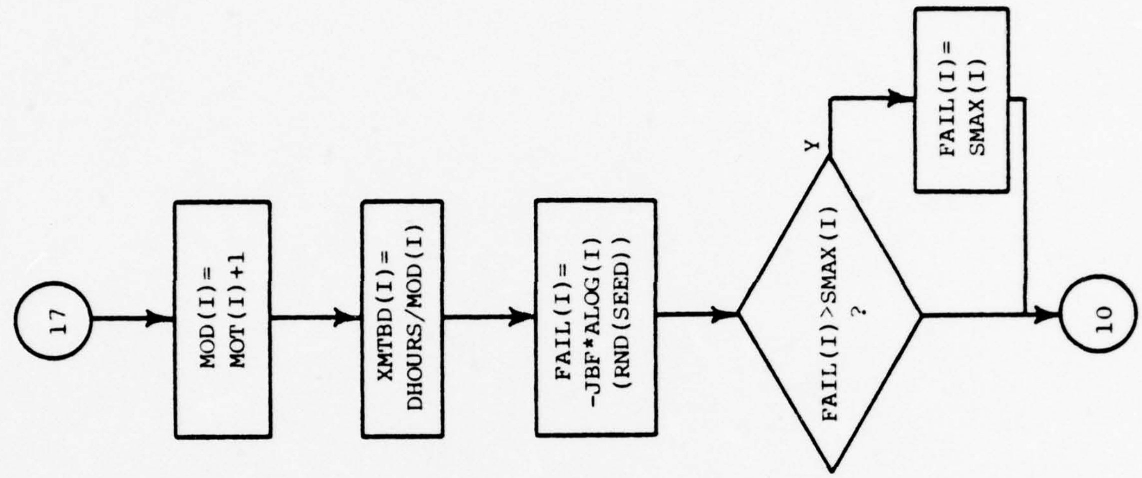

8
I=1
I>5?
I=I+1
I=JO
?
Y
10
FAIL(I)=
FAIL(I)-FAIL(JO)
FAIL(I)<.01
?
Y
10
12
10
Y
DHOURS>RUNHRS
?
Y
ENGMTBD
=DHOURS/
JENG
19
9


12
USED(I) = USED(I) + FAIL(JO)
13
19
JAP=1
JAP>5
JAP=JAP+1
SUMTA =SUMTA +PTACOST (JAP)
SNRT(JAP) = (JOPR(JAP) + OLDNRTS (JAP) *(MOD (JAP) -JOPR (JAP)) /MOD(JAP)
Y
18


13
SMAX(I)*PERC(I)
>
SMAX(I)-USED(I)
?
10
FAIL(I)<
SMAX(I)-
USED(I)
?
14
15
18
NO=1
NO>5?
NO=NO+1
FAIL(NO)=0
USED(NO)=0
MOD(NO) =0
SUM(NO) =0
PERC(NO) =0
XMTBD(NO) =0
PTACOST(NO)=0
SNRT(NO) =0
JOPR(NO) =0
Y
SUMTA
=0
21


14
SUM(I)= SUM(E)+ FAIL(I)
ICOUNT =FAIL(I)/ 50
15
SUM(I)= SUM(I)+ (SMAX(I)- USED(I))
SUM(I)= SUM(I)+ FAIL(I)
ICOUNT= (SMAX(I) -USED(I))/ 50
JCOUNT= DHOURS/50
16


16
JBACK=JCOUNT
JBACK>ICOUNT +JCOUNT
JBACK=JBACK+1
Y
PTACOST(I)= PTACOST(I)+ (50*COSTHR(I)
(1+PINT)JBACK
11
JOPR(I)=JOPR(I) +1
USED(I)=0
17


17
MOD(I)=
MOT(I)+1
XMTBD(I)=
DHOURS/MOD(I)
FAIL(I)=
-JBF*ALOG(I)
(RND(SEED))
FAIL(I)>SMAX(I)
?
Y
FAIL(I)=
SMAX(I)
10

APPENDIX B

FORTRAN IV SIMULATION PROGRAM

```
10*#RUN *=(ULIB)GRADLIB/TSS,R
20 DIMENSION FAIL(5),USED(5),SMAX(5),PERC(5),MOD(5),
30&JOPR(5),TBF(5),
40&XMTBD(5),SUM(5),PTACOST(5),COSTHR(5),OLDNRTS(5),SNRT(5)
50 PRINT,"GIVE ITERATIONS"
60 READ,ITER
70 DO 222 INT=1,ITER
80 TBF(1)=2353.
90 TBF(2)=2000.
100 TBF(3)=8000.
110 TBF(4)=2667.
120 TBF(5)=13333.
130 SMAX(1)=2160.
140 SMAX(2)=3600.
150 SMAX(3)=1920.
160 SMAX(4)=20000.
170 SMAX(5)=1000.
180 RUNHRS=480000.
190 COSTHR(1)=101483./SMAX(1)
200 COSTHR(2)=27402./SMAX(2)
210 COSTHR(3)=32858./SMAX(3)
220 COSTHR(4)=41000./SMAX(4)
230 COSTHR(5)=4225./SMAX(5)
240 OLDNRTS(1)=.29
250 OLDNRTS(2)=.30
260 OLDNRTS(3)=.30
270 OLDNRTS(4)=.13
280 OLDNRTS(5)=.33
290 SEED=-3.
300 PRINT,"GIVE PERC"
310 READ,PERC
320 PINT=.1*500./RUNHRS
330 35 JENG=0
340 DHOURS=0.
350 DO 2 IT=1,5
360 FAIL(IT)=-(TBF(IT))*ALOG(RND(SEED))
370 IF(FAIL(IT).GT.SMAX(IT))FAIL(IT)=SMAX(IT)
380 2 CONTINUE
390 6 JO=1
400 SAIL=FAIL(1)
```

```
DO 3 KO=2,5
IF(SAIL.LE.FAIL(KO))GO TO 3
SAIL=FAIL(KO)
JO=KO
3 CONTINUE
USED(JO)=0.
MOD(JO)=MOD(JO)+1
DHOURS=DHOURS+FAIL(JO)
JENG=JENG+1
XMTBD(JO)=DHOURS/MOD(JO)
DO 4 I=1,5
IF(I.EQ.JO)GO TO 4
FAIL(I)=FAIL(I)-FAIL(JO)
IF(FAIL(I).LT..01)GO TO 60
USED(I)=USED(I)+FAIL(JO)
IF((SMAX(I)*PERC(I)).GT.(SMAX(I)-USED(I)))GO TO 5
GO TO 4
5 IF(FAIL(I).LT.(SMAX(I)-USED(I)))GO TO 81
SUM(I)=SUM(I)+(SMAX(I)-USED(I))
ICOUNT=(SMAX(I)-USED(I))/50.
GO TO 103
81 SUM(I)=SUM(I)+FAIL(I)
ICOUNT=FAIL(I)/50.
103 JCOUNT=DHOURS/50.
DO 911 JBACK=JCOUNT,ICOUNT+JCOUNT
PTACOST(I)=PTACOST(I)+(50.*COSTHR(I)/((1.+PINT)**
&JBACK))
911 CONTINUE
82 JOPR(I)=JOPR(I)+1
60 USED(I)=0.
MOD(I)=MOD(I)+1
XMTBD(I)=DHOURS/MOD(I)
FAIL(I)=-(TBF(I))*ALOG(RND(SEED))
IF(FAIL(I).GT.SMAX(I))FAIL(I)=SMAX(I)
4 CONTINUE
IF(DHOURS.GT.RUNHRS)GO TO 15
FAIL(JO)=-(TBF(JO))*ALOG(RND(SEED))
IF(FAIL(JO).GT.SMAX(JO))FAIL(JO)=SMAX(JO)
GO TO 6
15 ENGMTBD=DHOURS/JENG
DO 47 JAP=1,5
SUMTA=SUMTA+PTACOST(JAP)
47 SNRT(JAP)=(JOPR(JAP)+OLDNRTS(JAP)*(MOD(JAP)-
&JOPR(JAP)))
&/MOD(JAP)
PRINT 16,ENGMTBD,XMTBD,SNRT,SUMTA
16 FORMAT(/"ENGMTBD",F19.0//"MTBD",5F10.0/"NRTS",
```

```
880&5F10.2
890&//"TOTAL PV OF DOLLARS THROWN AWAY",F20.0)
900 DO 69 NO=1,5
910 FAIL(NO)=0.
920 USED(NO)=0.
930 MOD(NO)=0.
940 SUM(NO)=0.
950 PERC(NO)=0.
960 XMTBD(NO)=0.
970 PTACOST(NO)=0.
980 SNRT(NO)=0.
990 69 JOPR(NO)=0.
1000 222 SUMTA=0.
1010 70 STOP
1020 END
```

APPENDIX C

CARDIN INPUT FOR MODMETRIC PROGRAM

```
10##NORM,R(SL)
20$:IDENT:WP1191,AFIT/SL,DUVALL GOETZ
30$:SELECTA:MODMETRIC/TWOIND,R
40$:LIMITS:15,40K
50$:DATA:05
90$:SELECTA:BASES1
100#98 0602
110#91 NBIS BETA BSTART BSTOP CFAC  PBINC
120#99 010  3.00  1.25  0.01  0.00  0.03
130$:SELECTA:RUN801
140$:ENDJOB
```

APPENDIX D

BASES1 FILE

70#97 002 2000.12. 2000. 9.

APPENDIX E

RUN801 FILE

30#21 F100 ENGINE	2180000	421.	.10	2	6	42
35#31 CORE	919900	1383.	.29	1	8	37
40#31 FAN	231000	1583.	.41	1	4	25
45#31 TURBINE	220100	1638.	.55	1	5	21
50#31 AUGMENTOR	470800	2722.	.13	1	4	24
55#31 GEARBOX	30500	637.	.84	1	3	18

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